METALS HANDBOOK

VOL. 6
WELDING AND BRAZING

8th EDITION

METALS HANDBOOK, eighth edition

- Vol. 1. Properties and Selection of Metals (1961)
- Vol. 2. Heat Treating, Cleaning and Finishing (1964)
- Vol. 3. Machining (1967)
- Vol. 4. Forming (1969)
- Vol. 5. Forging and Casting (1970)
- Vol. 6. Welding and Brazing (1971)
- Vol. 7. Metallography (in preparation)
- Vol. 8. Failure Analysis (in preparation)

Additional volumes are planned.

PRINCIPAL SUBJECTS

Arc Welding Processes and Their Application to Low-Carbon Steel

Arc Welding of:

Electroslag and Electrogas Welding

Resistance Welding

Flash and Friction Welding

Electron Beam Welding

Gas Welding

Brazing

METALS HANDBOOK

8th Edition

VOL. 6

Welding and Brazing

prepared under the direction of the

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FOREWORD

THE PUBLICATION of Volume 6, "Welding and Brazing", marks the crossing of the midpoint in the preparation of the ten-volume 8th Edition of METALS HANDBOOK, and the completion of the five volumes devoted to metalworking processes.

One of the continuing aims of industry is to increase the index of productivity from year to year. Volume 6, together with its companion volumes on other metalworking processes, can serve as a dependable guide to the adaptation of the most efficient and productive methods of fabricating metals. These books provide industry with reliable information on modern techniques for converting metals economically into useful products, and they can thus be helpful toward contributing to improvements in the index of productivity.

Volume 6 required the dedicated efforts of authors and author committees comprising more than 400 experts with broad experience and specialized knowledge in the fields of welding and brazing, and in the application of these joining processes to all commonly used metals and alloys. These experts were selected for this task by the Handbook Committee — a group of engineers and industrial managers who guide the planning of technical content and monitor the over-all editorial policy. The diligent and competent editorial staff coordinated and edited the information supplied by the authors into the well-organized and readily usable form in which it is presented in this book. To all these people — and to the many other contributors from industrial, academic, research and government organizations — the members of ASM, and all other users of this valuable reference book, owe sincere gratitude and appreciation.

The American Society for Metals takes pride in making available to the metalworking community Volume 6 of the 8th Edition of METALS HANDBOOK, and is confident that the information presented in these pages will be of great benefit to those concerned with modern technology and its application.

THOMAS E. LEONTIS
President – American Society for Metals

ALLAN RAY PUTNAM
Managing Director

PREFACE

THIS IS THE SIXTH in a series of volumes that will supersede the single-volume 7th edition of METALS HANDBOOK and greatly enlarge its scope. In preparing this new volume, the aim of the ASM Handbook Committee and the authors has been to provide the reader with practical information that will help him select and control welding and brazing processes and that will clarify many of the relations between product design and the control of welding and brazing processes.

The welding and brazing processes and the base metals discussed here are those most frequently used in the metalworking industry. Slightly more than half the book deals with arc welding; approximately two-thirds of the examples of practice that appear throughout the book are concerned with steel as the metal being welded or brazed.

The table below compares in detail the subject coverage in this sixth volume of the 8th edition with the coverage of corresponding subject matter in the 7th edition.

The principal new contribution made in this volume is the multiplicity of examples that describe welding and brazing practices. Numbered consecutively from 1 through 661 from the front to the back of the book, these examples deal with the methods and procedures used, and with improvements made or problems solved, in specific applications; and they emphasize the results obtained in joining a great variety of assemblies and structures. Many cross references are given in the text, and in tables at the ends of some articles, to direct the reader to related examples presented elsewhere in the book. To make it easy to find any of the 661 examples, the span of example numbers presented on each pair of facing pages is indicated at the tops of those pages, near the inside margins.

As it was for the first five volumes of this 8th edition, principal reliance for authorship has again been placed on committees of engineers and production managers from industry, in order to arrive at a balanced presentation of divergent viewpoints and to achieve realism in relation to practice. Of the 31 committees participating in this volume, 18 contributed on specific assigned subjects. Rosters of the members of these 18 author committees are presented or referred to on the first pages of the articles to which they contributed. The remaining 13 committees were concerned with welding and brazing applications without restriction as to proc-

Coverage of Welding and Brazing in Volume 6 of the 8th Edition Compared With That in the 7th Edition

Section (page reference, 8th edition)	Illustrations 8th ed	Illustrations 7th ed	Tables 8th ed	Tables 7th ed	Examples 8th ed	Examples 7th ed	Contributors 8th ed	Contributors 7th ed	Pages 8th ed	Pages 7th ed
Welding										
Arc welding processes and their application to low-carbon steel (1 to 186)	1058	3	239	2	180	0	162	7	186	13
Arc welding of metals other than low-carbon steel (187 to 382)	1019	4	305	8	180	0	184	16	196	12
Electroslag and electrogas welding (383 to 400)	74	0	9	0	9	0	5	0	18	0
Resistance welding (401 to 484)	335	12	89	2	60	0	94	3	84	3
Flash and friction welding (485 to 518)	177	0	40	0	34	0	22	0	34	0
Electron beam welding (519 to 564)	261	0	59	0	42	0	21	0	46	0
Gas welding (565 to 592)	147	4	34	3	38	0	41	3	28	4
Total for welding	3071	23	775	15	543	0	529	29	592	32
Brazing										
Brazing processes and their application to carbon and low-alloy steels (593 to 660)	373	2	40	3	68	0	26	3	68	4
Brazing of metals other than carbon and low-alloy steels (660 to 702)	197	0	44	3	50	0	58	4	42	3
Total for brazing	570	2	84	6	118	0	84	7	110	7
Total for welding and brazing	3641	25	859	21	661	0	613	36	702	39

Each member of an applications committee (see pages v and vi) is included in all sections to which he contributed. Members of author committees that contributed to more than one section are included in each. Eliminating duplications from these sources reduces the total number of contributors from 613 to approximately 400.

Distribution of Subject Matter on Metalworking Processes in Volumes 2 Through 6 of the 8th Edition

Metalworking process	Illustrations No.	Illustrations %	Tables No.	Tables %	Examples No.	Examples %	Contributors No.	Contributors %	Pages No.	Pages %
Welding (Volume 6)	3,071	22.8	775	20.3	543	15.4	529	23.6	592	21.0
Machining (Volume 3)	2,836	21.1	1099	28.8	1009	28.7	348	15.5	512	18.1
Forming (Volume 4)	2,957	21.9	477	12.5	705	20.0	306	13.7	496	17.6
Cleaning and finishing (Volume 2)	515	3.8	578	15.2	336	9.5	433	19.3	362	12.8
Heat treating (Volume 2)	1,193	8.9	377	9.9	311	8.8	339	15.1	306	10.8
Casting (Volume 5)	1,391	10.3	292	7.7	353	10.0	133	5.9	300	10.6
Forging (Volume 5)	944	7.0	130	3.4	147	4.2	68	3.1	148	5.2
Brazing (Volume 6)	570	4.2	84	2.2	118	3.4	84	3.8	110	3.9
Total	13,477	100.0	3812	100.0	3522	100.0	2240	100.0	2826	100.0

ess or metal; they contributed a total of more than 300 examples of practice, which are distributed in the pertinent articles throughout the book. Rosters of the members of these 13 applications committees appear on pages v and vi in this volume.

Simon A. Greenberg, welding consultant, San Francisco, was retained as a manuscript reviewer and technical editor for this volume. He reviewed the manuscripts and proofs of the entire book, and has been responsible for many improvements in technical content, editorial presentation, and general clarity. Because of the importance of his contribution to this volume, Mr. Greenberg is listed on the title page as engineering editor.

Other individuals, not named on the title page, made significant contributions in reviewing manuscripts and galley proofs: Jay Bland, M. L. Both, E. B. LaVelle and N. H. Mason each reviewed approximately half the book; from five to ten articles each were reviewed by D. E. Brown, J. D. Eyestone, R. L. Harris, A. N. Kugler, B. D. Lawrence and J. G. McArdle; D. C. Dilley reviewed the nine articles on brazing, in manuscript and proof; others, too numerous to list, have participated in the review of several articles each. We are grateful to all the reviewers; their work has increased the accuracy and clarity of the volume, and has provided greater unity and consistency among disparate contributions than would have been possible under a review procedure in which each article was read only by the author committee that was responsible for its preparation. In addition to their other contributions, the reviewers have helped to bring the technical terminology in this book into closer agreement with AWS A3.0-69 (Terms and Definitions, American Welding Society, 1969).

PUBLICATION of this book completes the five volumes of the 8th edition that are concerned with metalworking processes. In the order presented, these processes are: heat treating, cleaning, finishing, machining, forming, forging, casting, welding and brazing. A decade has been required for compiling and publishing these volumes. The table above summarizes numerically the results of this work, listing the processes by decreasing number of pages the subjects occupy in the five volumes. Preparation of the 2826 pages involved the participation of more than two thousand contributors. Upon the collective experience and high competence of these contributors rest the accuracy and authority of the information in those pages.

TAYLOR LYMAN
Editor – Metals Handbook

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WELDING

Arc Welding Processes and Their Application to Low-Carbon Steel

Arc Welding of Metals Other Than Low-Carbon Steel

Electroslag and Electrogas Welding

Resistance Welding

Flash and Friction Welding

Electron Beam Welding

Gas Welding

BRAZING

ARC WELDING PROCESSES AND THEIR APPLICATION TO LOW-CARBON STEEL

CONTENTS

Shielded Metal-Arc Welding

*By the ASM Committee on Shielded Metal-Arc Welding of Steel**

SHIELDED METAL-ARC WELDING is a manual arc welding process in which the heat for welding is generated by an arc established between a flux-covered consumable electrode and the work. The electrode tip, weld puddle, arc, and adjacent areas of the workpiece are protected from atmospheric contamination by a gaseous shield obtained from combustion and decomposition of the flux covering. Additional shielding is provided for the molten metal in the weld puddle by a covering of molten flux (slag). Filler metal is supplied by the core of the consumable electrode and, with certain electrodes, from metal powder mixed with the electrode covering. Shielded metal-arc welding is often referred to as arc welding with stick electrodes, and as manual arc welding.

Process Capabilities

Shielded metal-arc welding is the most widely used welding process for joining metal parts, mainly because of its versatility. Also, equipment is less complex, more portable and less costly than for other arc welding processes.

Versatility. Shielded metal-arc welding can be done indoors or outdoors. Joints in virtually any position that can be reached with an electrode (for example, joints directly overhead and vertical joints) can be welded. By the use of bent electrodes, even joints in blind areas can be welded — for example, the back sides of pipes in restricted areas, which are inaccessible locations for most welding processes.

Joints in almost any location can be welded, because the power-supply leads can be extended for relatively long distances and no hoses are required for shielding gas or water cooling. Some locations where shielded metal-arc welding has been used in the field are storage tanks, ship structures, and bridges. Machinery or other equipment in manufacturing plants and in remote areas such as oil fields can be repaired by use of the process, because the welding equipment is light and portable.

Shielded metal-arc welding is generally more useful than other welding processes for joining the components of complex structural assemblies, because it is better adapted to multiposition welding and difficult locations. In the assembly of pipe and coupling connections, joints that have been prepared for automatic or semiautomatic equipment may not fit when the assembly is fitted to a machine. When this occurs, it is a simple and quick procedure to gas cut the assembly apart, adjust it in place to fit properly, tack weld it, and then weld the complete assembly by the shielded metal-arc process. For this type of work, other welding processes may require more extensive dismantling of the structure.

Welded joints can be cut apart on location and rebuilt with added structural members — a practice that is often necessary, particularly in operations such as well drilling, quarrying and mining.

Joint Quality and Strength. The quality and strength of shielded metal-arc welded joints can be controlled as easily as the quality and strength of joints welded by other manual methods that employ consumable electrodes. Shielded metal-arc welding electrode materials are available for matching the properties of most base metals. Thus, the properties of a joint can match those of the metals joined.

Metals welded most easily by the shielded metal-arc process are carbon and low-alloy steels, stainless steels and heat-resisting alloys.

Cast iron, and the high-strength and hardenable types of steel, can also be

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O. H. KUHLKE, Director of Welding Laboratory, General American Transportation Corp.; D. H. MARLIN, Research Engineer, Dravo Corp.; ARJAY W. PLATT, Quality Assurance Manager, Caterpillar Tractor Co. Ltd.; H. F. REID, Assistant to Vice President, McKay Co.; HOWARD E. BOYER, *Secretary*, Managing Editor, Metals Handbook.

Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees. A total of 70 examples of shielded metal-arc welding appear in other articles in this volume, as recorded in Table 16, on page 23.

Table 1. Output Ratings of Power Supplies Used in Shielded Metal-Arc Welding

Output current, amp, at load, volts — Rated (60% duty cycle)(a)	Maximum (35% duty cycle)(b)
Constant-Current Motor-Generators (DC)	
300 at 32	375 at 35
400 at 36	500 at 40
500 at 40	625 at 44
600 at 44	750 at 44
Transformer-Rectifiers (DC)	
400 at 36	500 at 40
500 at 40	625 at 44
600 at 44	750 at 44
800 at 44	1000 at 44
Transformers (AC)	
400 at 36	500 at 40
500 at 40	625 at 44
600 at 44	750 at 44
(One-hour duty rating)(c)	(35% duty cycle)(b)
750 at 44	925 at 44
1000 at 44	1250 at 44
1500 at 44	1875 at 44

(a) Rated current can be delivered continuously for 6 min out of every 10 min. (b) Maximum current can be delivered continuously for 3½ min out of every 10 min. (c) Rated current can be delivered continuously for 1 hr, then for 45 min of every hour for the next 3 hr.

shielded metal-arc welded, but procedures that include preheating or postheating, or both, may be needed. Electrode selection and care are more critical for welding hardenable steels.

Copper alloys and nickel alloys are often welded by the shielded metal-arc process, although gas metal-arc welding and gas tungsten-arc welding are usually preferred and are more widely used for joining these metals.

The softer metals such as zinc, lead and tin, which have low melting and boiling temperatures, are not amenable to shielded metal-arc welding.

The use of shielded metal-arc welding for joining of metals other than low-carbon steel is discussed elsewhere in this volume, in articles that deal with the welding of specific metals.

Limitations of shielded metal-arc welding compared with other arc welding processes, such as gas metal-arc and submerged-arc welding, are related mainly to metal-deposition rate and deposition efficiency. Electrodes used in shielded metal-arc welding have fixed lengths (usually 18 in. or less), and therefore welding must be stopped after each electrode is consumed. With the arc welding processes that use continuously fed electrode wires or no filler metal, welding can be done much longer without interruption.

Another limitation of shielded metal-arc welding is that deslagging is required after each pass, to remove the slag covering that forms on the weld. In gas metal-arc welding, multiple passes can be made without stopping for slag removal, since no flux is used.

Principles of Operation

An adequate power supply is the first requirement for shielded metal-arc welding. To prepare for welding, suitable cables are used to attach one terminal of the power supply to the electrode holder, and the other terminal to a ground clamp, as shown in Fig. 1.

To start welding, an arc is "struck" by touching the workpiece with the tip of the electrode — much like striking a match. The welder guides the electrode by hand in welding a joint, and controls its direction and travel speed. The welder maintains arc voltage by controlling arc length — the distance between the end of the electrode and the work surface. In many applications in which electrodes with heavy coverings are used, the welder actually drags the electrode in the joint or on the work and uses the electrode angle to control arc length. Electrodes are discarded at a length of about 2 in.

Electrically, the process is simple in concept; a power supply with a drooping volt-ampere characteristic is required. With it the current decreases as the arc becomes longer, and increases as the arc becomes shorter.

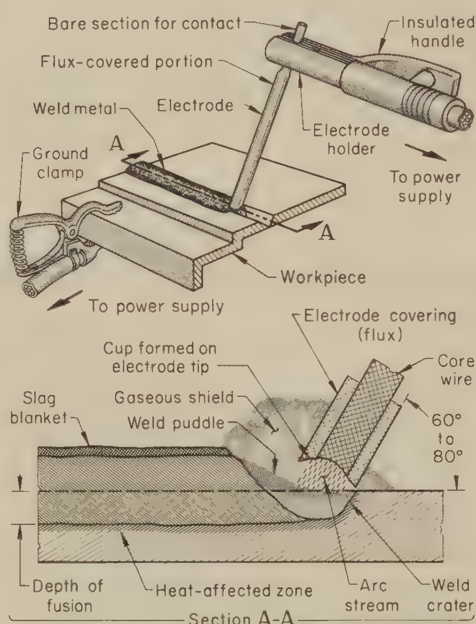


Fig. 1. Typical setup and fundamentals of operation for shielded metal-arc welding

Table 2. Space Requirements, Output Ranges, and Costs of AC and DC Power Supplies for Shielded Metal-Arc Welding

Typical floor space required, in.	Typical output range, amp	Typical cost
Light-Duty Transformers (AC)		
14 by 14	30 to 180	$ 125
	35 to 295	230
Heavy-Duty Transformers (AC)		
22 by 29	50 to 375	$ 280
	50 to 625	320
28 by 45	100 to 1300	2139
Light-Duty Motor-Generators (DC)		
18 by 26	40 to 260	$ 439
Heavy-Duty Motor-Generators (DC)		
19 by 36	30 to 450	$ 685
19 by 39	40 to 600	815
19 by 42	50 to 800	1029
Transformer-Rectifiers (DC)		
21 by 39	25 to 425	$ 567
24 by 44	25 to 525	630
Heavy-Duty Transformer-Rectifiers (DC)		
22 by 39	40 to 375	$ 505
	50 to 625	635
Gasoline-Engine Generators (DC)		
31 by 75 (52 hp)	30 to 450	$1640
(69 hp)	30 to 600	1730
(85 hp)	40 to 800	1995

However, the basically simple concept is complicated by the effect of transfer of metal across the arc, which can short-circuit the power supply. As a result, the dynamic characteristics of the power supply are all-important; the reactance of the circuit that controls the speed of current response to short circuits affects the drop size and stability of the arc.

Electrode Coverings. The chemical and metallurgical properties of a weld depend mostly on the type of electrode to be used and its type of covering.

Oxygen and nitrogen in the atmosphere can cause excessive porosity and poor ductility in the welded joint if they are not excluded from the weld puddle. In shielded metal-arc welding, combustion and decomposition of the electrode covering from the heat of the welding arc produce a gaseous shield that excludes the atmosphere from the weld area. The molten metal is further protected by materials in the electrode covering that form a molten slag, which acts like a protective blanket until the metal has solidified (Fig. 1). Most electrode coverings also contain deoxidizers and nitrogen absorbers.

The electrode covering also provides materials such as sodium and potassium that are readily ionized when heated by the arc. These help to keep the gap between the end of the electrode and the workpiece conductive and to stabilize the arc.

The electrode covering also may be used to introduce alloying additions into the weld. Most electrodes used for welding low-carbon steel have a plain carbon steel core, but alloying elements are sometimes added from the covering. Some coverings contain iron powder, which increases metal-deposition rates.

The electrode covering provides a cuplike shape at the end of the electrode (see section A-A in Fig. 1). This cup acts like a nozzle, increasing thermal efficiency and providing arc-stream direction, which helps the welder to direct the transfer of metal from the electrode into the weld puddle.

The usability characteristics of an electrode, such as speed of deposition, variety of possible welding positions, shapes of weld beads, ease of slag removal, and properties of the weld, are controlled by the design and chemical formulation of the electrode covering.

Welding Positions. The usual welding positions are flat, horizontal, vertical and overhead, as shown for groove and fillet welds in Fig. 2. In some welding, the positions of the hours on a clock are used as reference locations.

The flat position is the easiest for welding. In this position, welding benefits from the force of gravity, and maximum deposition rates are obtained. Next in ease of welding is the horizontal fillet position, in which the force of gravity helps to some extent. For welding in these positions, the joint should be level, or nearly so, when possible (see also "Positioning", page 11).

Welding in positions other than flat (frequently referred to as out-of-position welding) requires the use of manipulative techniques and electrodes that result in faster freezing of the molten metal and slag, to counteract the effect of gravity.

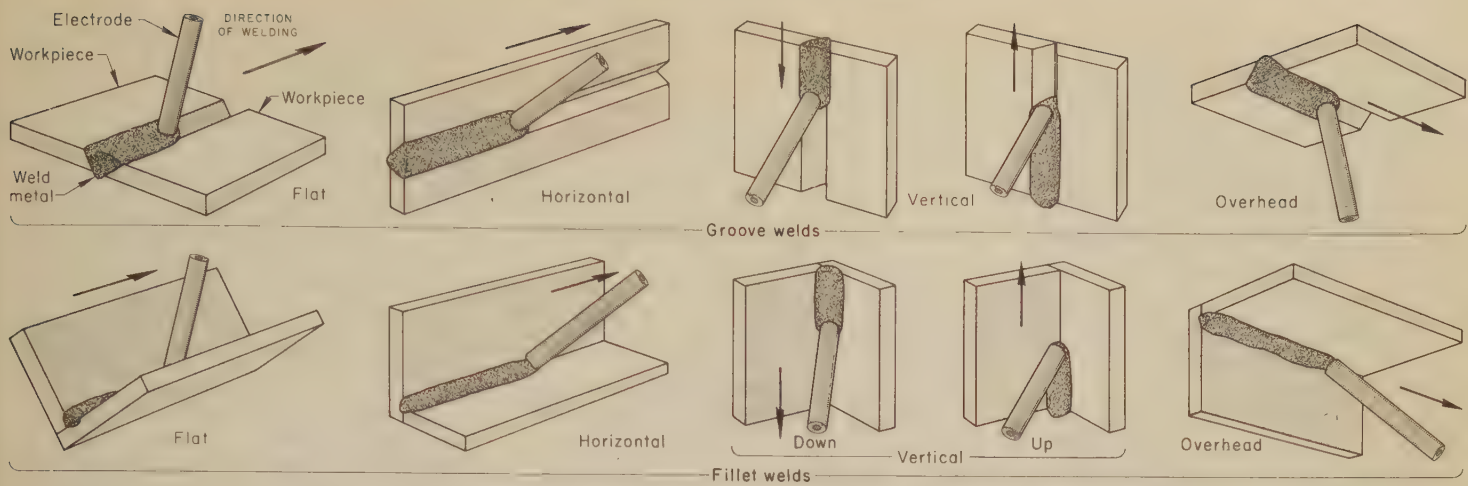


Fig. 2. Usual welding positions, for making groove welds (top row) *and fillet welds* (bottom row)

Power Supplies

Many types and sizes of power supply are used for shielded metal-arc welding. When alternating current is used, high-voltage power is transformed or stepped down through a welding-type transformer to a voltage low enough for safe use. When direct current is used, a generator or a transformer-rectifier unit is used. A transformer-rectifier consists of a step-down-voltage transformer with means to rectify alternating current to direct current.

Either alternating current or direct current can produce acceptable results in welding low-carbon steel. Although each has distinct advantages, the choice usually depends on availability of equipment and the type of electrode to be used. The sections on Direct Current, on page 5, and Alternating Current, on pages 5 and 6, deal with the characteristics, advantages and disadvantages of these currents.

Combination ac/dc power supplies are widely used and are versatile for general-purpose applications. They consist of a transformer and a rectifier in combination and are capable of supplying either alternating current or direct current. When direct current is used, either straight or reverse polarity is available. Output ratings for various power supplies are given in Table 1.

Constant-Current Output. In general, power supplies with constant-current output and a means of controlling current output are required for shielded metal-arc welding. Constant-current output is obtained with a drooping volt-ampere characteristic; that is, voltage within a specified range is reduced as current increases. Figure 3 shows a typical curve for voltage versus current output. Constant-current output is preferred because small variations in voltage caused by variations in arc length do not significantly affect the current output and deposition rate. For instance, the dashed lines in Fig. 3 show that a 3-volt drop in voltage results in only about a 10-amp increase in current output.

Selection Factors. Factors that influence the selection of power supply include available power, available floor space, initial costs, location of the operation (in a plant or in the field), personnel available for maintenance, versatility, required output, duty cycle, efficiency and type of electrodes to be used. Table 2 gives typical space requirements, outputs and initial costs for power supplies. Efficiency of power supplies in terms of power costs and melting and deposition rates is discussed on page 4.

The deposition rate desired determines, to a great extent, the output required from a power supply. The deposition rate obtained, however, is related to the duty cycle, capacity and efficiency of a power supply. (See "Efficiency of Power Supplies", page 4.)

The duty cycle of a power supply is the percentage of time, calculated on several successive 10-min periods, during which it can operate at full capacity without exceeding recommended maximum operating temperature. If a power supply is operated at its rated capacity but beyond its rated duty cycle, overheating will occur, possibly resulting either in no welding at all or, if the power supply is of the rectifier type, in burning-out of the plates. Overheating will occur also if a power supply is operated beyond its capacity, unless the duty cycle is reduced. However, short periods of overloading are not usually harmful to constant-current power supplies; for example, a duty cycle of 76% can be permitted for short periods on a power supply rated at 60%. Table 1 gives dc and ac output ratings for duty cycles of 60% and 35%, and ac output ratings for 1-hr duty.

Transformers for shielded metal-arc welding with alternating current generally have constant-current (drooping) volt-ampere characteristics (Fig. 3). Although heavy-duty transformers

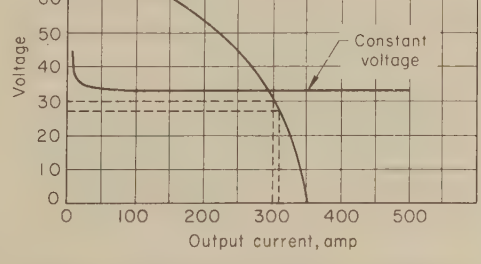


Fig. 3. Volt-ampere curves for constant-current and constant-voltage power supplies

Table 3. Effect of Duty Cycle and Power Factor on Power Cost for a 300-Amp Transformer (a)

Duty cycle(b)	Power cost, $, at a power factor of: 60%	70%	80%	90%
20%	$2.33	$1.40	$1.40	$1.40
40%	4.66	2.80	2.80	2.80
60%	7.00	5.65	4.20	4.20
80%	9.32	7.56	6.20	5.60

(a) Costs are monthly demand charges calculated at 50¢ per kva for a 300-amp transformer that is operating at rated load. (b) Percentage of time transformer is in operation.

with outputs up to 1500 amp are available, transformers with ratings of 200 to 500 amp are most often used in industrial welding applications. Transformers with ratings of less than 200 amp are used extensively in farm and job-shop applications, because they can be operated with 220-volt power and usually have sufficient capacity.

Transformers have lower initial costs than direct-current power supplies (Table 2). Also, they are more economical in terms of cost of power (see "Efficiency of Power Supplies", on page 4), and arc blow is minimized (see "Arc Blow", on page 10).

Poor power factor is inherent in the use of transformers of the constant-current type. Welding characteristics are not affected by a poor power factor, but power cost is increased (as shown in Table 3). For this reason, correcting capacitors can be used to reduce operating costs.

Some plants have, in addition to transformers, electric motors such as large synchronous motors that operate air compressors and other equipment. These motors have a favorable influence on power factor and therefore help to keep the plant power factor within acceptable limits. Under these conditions, welding transformers without power-factor correction are satisfactory. However, in plants where a major portion of the total consumption of electricity is by welding transformers, or where the reserve capacity is inadequate, transformers with power-factor correction should be chosen.

Table 3 shows the effect of power factor and duty cycle on power cost for a 300-amp transformer. The costs are calculated at a utility rate of 50¢ per kva of demand per month, but actual costs vary according to local rates. As shown in Table 3, power cost

is generally proportional to duty cycle and, especially at high duty cycle, decreases as the power factor increases.

Motor-generators and transformer-rectifiers are power supplies for welding with direct current. Most of these dc machines have constant-current (drooping) volt-ampere characteristics. A constant-voltage power supply—that is, one that has nearly constant voltage output with increasing current output (see Fig. 3)—is not well suited to shielded metal-arc welding, because the volt-ampere curve does not have sufficient droop to compensate for variations in arc voltage.

The motor-generators most widely used in industry for shielded metal-arc welding have outputs of 200 to 600 amp. However, units having much larger capacities are available.

Engine-driven generators can be used in the shop or field where no line power supply is available.

Maintenance costs for motor-generators are higher than for transformer-rectifiers. All motor-generators have some moving parts that require periodic repair or replacement. Engine-driven generators have more moving parts and high initial cost (Table 2).

Other factors being equal, direct-current power supplies that have outputs with the same percentages of ripple (superimposed alternating current) will have the same performance. A relatively pure direct-current output is desirable, but all direct current except that from a battery has some ripple. The current from a motor-generator has a ripple content of up to 6%, which is created as the brushes collect the current from the commutator. Transformer-rectifiers also produce current containing alternating-current ripple. With conventional three-phase transformer-rectifiers, ripple content of 20 to 30% has been observed, although it is more often nearer 6%.

A transformer-rectifier does not produce a uniform direct current and can give ammeter readings different from those obtained with a motor-generator of the same rated capacity. When high-amperage current is used, a transformer-rectifier may require adjustments so as to give melting or deposition rates equal to those obtained with motor-generators. Melting and deposition rates obtained by the use of motor-generators and transformer-rectifiers are compared in the next section, "Efficiency of Power Supplies".

Most motor-generators and transformer-rectifiers have switches that permit current to be supplied with either straight polarity (electrode negative) or reverse polarity (electrode positive), without the need for disconnecting and reconnecting cables. This facility is advantageous in applications that involve a wide range of work metals and electrode types. (See the section on Direct Current, page 5.)

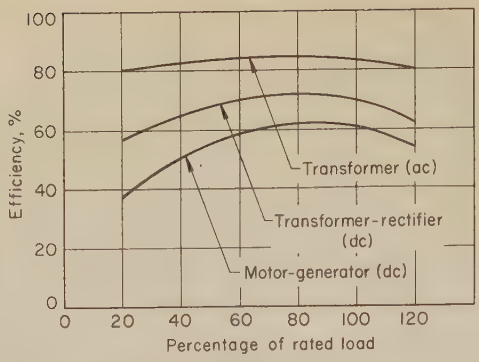


Fig. 4. Effect of operating load (as a percentage of rated load) on efficiency of three types of power supplies

Efficiency of Power Supplies

Efficiencies of power supplies can be compared in terms of (*a*) cost of power for current output, (*b*) melting rate, and (*c*) deposition rate.

Cost of electric power is significant in welding, but usually is a relatively small fraction of the total direct cost.

A motor-generator is the least efficient power supply in terms of cost of power for current output, because a large mass is continually rotated, even when welding power is not being used. Transformer-rectifiers and transformers operate at higher efficiencies, because they have no moving parts except cooling fans, and their no-load power loss is negligible. Their higher efficiency is especially significant when duty cycles are low. Even at high duty cycles, however, the efficiency of motor-generators does not match that of transformer-rectifiers or transformers.

Table 4. Power Costs for Three Types of Power Supply Operated at 300-Amp Output for Various Duty Cycles(a)

Power supply	Power cost for duty cycle of: 20%	40%	60%	80%
Motor-generator(b)	$0.80	$1.25	$1.71	$2.19
Transformer-rectifier	0.47	0.87	1.28	1.70
Transformer	0.38	0.71	1.05	1.37

(a) Power cost per unit, calculated at 1½¢ per kwhr for a 9-hr shift. (b) Electrically driven.

Efficiencies are always measured at rated load with arc or resistance loads and therefore represent actual operating conditions. Figure 4 compares efficiencies of a transformer, a transformer-rectifier, and a motor-generator, operating at 20 to 120% of rated load. The curves show that the motor-generator is least efficient, the transformer-rectifier is next, and the transformer is most efficient. Similar conclusions can be drawn from Table 4, which compares power costs for a motor-generator, a transformer-rectifier, and a transformer, each operated at 300-amp output for various duty cycles over a 9-hr shift.

Although direct-current power supplies are less efficient, in terms of power cost, than alternating-current supplies, direct current is usually the better choice when power is needed for many different base metals and electrodes (see the sections on Direct Current, page 5, and Alternating Current, pages 5 and 6).

Melting rate, or burnoff rate, is the rate at which an electrode of a specific type and size is melted by a specific welding current. It is usually expressed in inches per minute. Figure 5(a) compares melting rates for five different sizes of E6012 electrodes at five levels of current supplied by a transformer, a transformer-rectifier, and a motor-generator. Average melting rate with the motor generator was 7.7% higher than that with the transformer-rectifier, and 12.4% higher than that with the transformer.

For a given power supply, the melting rate of an electrode increases as current is increased. Figure 6 shows the effect of current supplied by a transformer and by a transformer-rectifier on the melting rate of five sizes of E6012 electrodes. The melting rate increases rapidly as the current is increased, especially for smaller-diameter electrodes. When welding current is too high, however, electrode deposition efficiency decreases rapidly because of arc blow, weld spatter and excessive heating of the electrode.

Deposition rate, expressed in pounds per hour or minute, is a direct measure of the amount of weld metal produced under a given set of conditions. Deposition rates for five sizes of E6012 electrodes used with a transformer, a transformer-rectifier, and a motor-generator are given in Fig. 5(b). Here, the deposition rates for the three power sources are essentially in the same order as the melting rates in Fig. 5(a), with the deposition rate for the motor-generator being highest. Calculations from the data in Fig. 5 show average deposition rate with the motor-generator to be 8.8% greater than with the transformer-rectifier, and 15.1% greater than with the transformer.

Deposition rate of an electrode is always less than melting rate because of losses by spatter and fume. The ratio of deposited weight to melted weight times 100 is the electrode efficiency.

Arc blow sometimes offsets the efficient operation of motor-generators at high welding currents. To overcome arc blow, the current must sometimes be decreased, as discussed in the section on Arc Blow (see page 10).

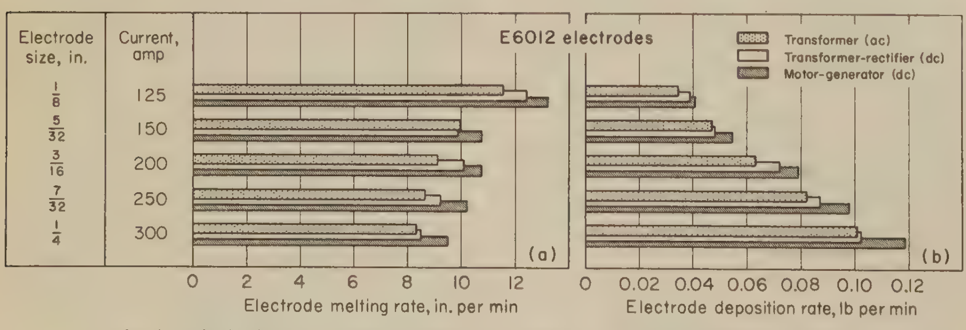


Fig. 5. Effect of type of power supply on melting rate and deposition rate of various sizes of E6012 electrodes at five levels of welding current

Variations in performance among different power supplies of the same general type must be considered when efficiencies are evaluated. For example, performance tests have shown that deposition rates at given currents for transformer-rectifiers from five different manufacturers varied 11% and that melting rates for the same equipment varied 9%.

Variations in electrode melting and deposition rates among different types of power supplies are a result of differences in electrical characteristics and types of electrodes.

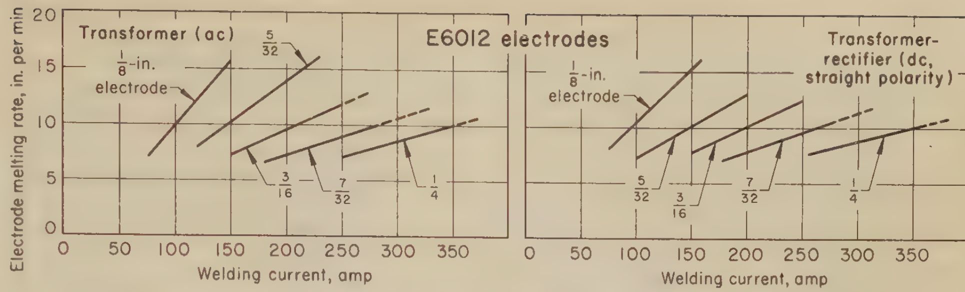


Fig. 6. Effect of level of welding current and type of power supply on melting rate of five sizes of E6012 electrodes

Direct Current

Direct current flows continuously in one direction through the welding circuit. Whether the current is uniform or fluctuating will not affect its direction, for any given welding setup. Because the current flow is continuous, the welding arc is relatively steady and smooth. The principal characteristics of direct current, and some important aspects of its use in shielded metal-arc welding, are discussed in the paragraphs that follow.

Voltage Drop in Cables. Welding cables should be as short as possible. Cable length is more critical for direct current than for alternating current. The voltage drop in long cables, added to that at the arc, can either overload the power supply, or prevent it from producing enough voltage for a proper welding arc.

Low Currents. Direct current surpasses alternating current for use at low amperages with small-diameter electrodes.

Electrodes. All classes of covered electrodes are satisfactory for use with direct current.

Arc starting is generally easier with direct current than with alternating current, particularly with small-diameter electrodes.

Maintaining a short arc, when the arc must be crowded into the molten puddle, is easier with direct current than with alternating current.

Arc Blow. Direct current is highly susceptible to arc blow, particularly when welding is being done near the ends of joints, in corners, or on small, complex structures composed of a number of pieces. Welding on massive structures with high currents, or where fit-up is poor, also encourages arc blow. Arc blow causes excessive weld spatter (see the section on Arc Blow, page 10).

Welding Positions. Direct current is somewhat easier to use for out-of-position welding on thicker sections than alternating current, because lower currents can be used. Experienced welders usually can produce the same results with both types of current.

Welding of Sheet Metal. Because of the steady, easily started arc, direct current is preferable to alternating current for welding of sheet metal.

Polarity (direction of current flow) is important when direct current is used for welding. Most dc power supplies have switching arrangements for reversing the polarity of the welding current whenever required. Current flow for straight polarity (electrode negative) and reverse polarity (electrode positive) is illustrated in Fig. 7.

Type of electrode, metal being welded, and required penetration are important factors in the choice of polarity. Some electrodes are specially made for deep penetration and work best with reverse polarity. Other electrodes are designed for shallower penetration and work better with straight polarity. (See the section on Electrodes, page 6.)

Straight polarity can be used for shielded metal-arc welding of all steels (except when using low-hydrogen electrodes), but not for most nonferrous metals. Melting and deposition rates are higher than with reverse polarity, and penetration is shallower and narrower (see Fig. 8). The contractional stresses are less severe, and restraint cracking is less likely. Also, because more of the heat is concentrated on the electrode, welding is more rapid with straight polarity and the workpiece is less susceptible to distortion. In addition, higher welding speed is usually possible with straight polarity.

Straight polarity is preferred for welding sheet metal, because the shallow penetration minimizes melt-through in thin sections. It is also preferred over reverse polarity for welding joints with excessively wide gaps or root openings, and for buildup.

Reverse polarity produces maximum penetration for a given set of welding conditions. Although the welding current is the main determinant of the extent of penetration, electrodes operating on reverse polarity provide deeper penetration than those operating on either straight polarity or alternating current (Fig. 8). This characteristic makes reverse polarity the better choice for root passes in groove welds made with the use of backing bars or strips, and for out-of-position welding.

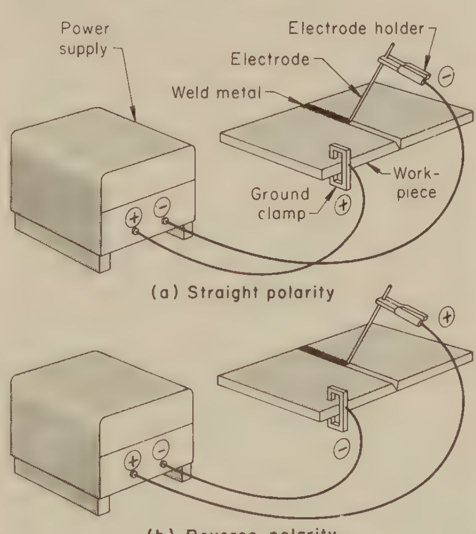


Fig. 7. Current flow for straight polarity (electrode negative) and reverse polarity (electrode positive)

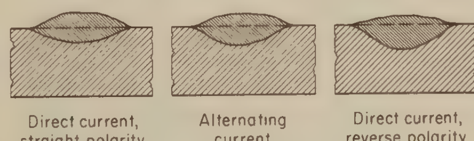


Fig. 8. Typical relative depths of penetration for different current characteristics

Alternating Current

Alternating current combines both reverse and straight polarity alternately in regular cycles. In each cycle, the current starts at zero, builds up to its maximum value in one direction, decays to zero, builds up to its maximum value in the opposite direction and decays to zero again. Cycles are repeated continuously while the welding arc is maintained. For the 60-cycle alternating current normally used in the United States, the direction of flow, and hence the polarity, changes 120 times each second. These changes produce a very rapidly pulsating arc that is somewhat harsh and less stable, compared with a direct-current arc.

Deposition rates and depth of penetration obtained with alternating current are intermediate between those obtained with reverse-polarity and straight-polarity direct current, when welding at the same current rating (see comparison of depths of penetration in Fig. 8). All electrodes that operate well on alternating current will operate on direct current with either reverse or straight polarity, although one polarity is usually recommended or preferred.

Some specific characteristics of alternating current, and aspects of its use in shielded metal-arc welding, are discussed in the paragraphs that follow.

Voltage Drop in Cables. Alternating current is preferred to direct current for welding that must be done at considerable distances from the power supply, because voltage drop is less than for direct current in long cables. Long cables should not, however, be coiled excessively, either on the floor or over hooks, because the inductance set up by the coils will reduce the output of the power supply, and may overload the transformer. Cables should never be longer than required for the job.

Low Currents. Alternating current is less suited than direct current for use at low amperages with small-diameter electrodes.

Electrodes. Only ac/dc electrodes with coverings specifically formulated for use with alternating current should be used. Because of the reversing nature of the current, coverings must contain arc stabilizers to re-establish the arc immediately after the current decays to zero during each cycle.

Arc starting with small-diameter electrodes is more difficult with alternating current than with direct current. When the arc is struck by the use of low current, electrodes may stick or freeze unless designed specifically for alternating-current welding with low open-circuit voltages.

Maintaining a short arc (arc crowding) is more difficult with alternating current than with direct current except when iron-powder electrodes are used.

Arc blow is rarely a problem with alternating current. The reversing nature of the

current causes the magnetic field in the work to build up and decay alternately in opposite directions, and thus neutralizes the magnetic field. (See the section on Arc Blow, on page 10.)

Weld Spatter. Somewhat more weld spatter is produced than with direct current, partly because of the pulsating nature of alternating current.

Welding Positions. With the use of suitable electrodes, satisfactory welds can be made in all positions.

Welding of Sheet Metal. Alternating current, because of the difficulty in arc starting, is generally less desirable than direct current for the welding of sheet metal (see "Arc starting", column 3, page 5).

Welding of Thick Sections. Alternating current is well suited for welding of thick sections by the use of large-diameter electrodes and maximum currents, because arc blow is seldom serious. In flat-position welding of heavy plate, maximum deposition rates can be obtained if suitable electrodes are used.

Electrodes

Electrodes used in shielded metal-arc welding have many different compositions of core wire and a wide variety of types and weights of flux covering.

This section deals mainly with electrodes for shielded metal-arc welding of low-carbon steel; electrodes for welding of other metals are dealt with in articles on welding of specific metals in this volume.

Standard electrode diameters (diameters of the core wire) range from 1⁄16 to 5⁄16 in. Length is usually 9 to 18 in., although electrodes up to 36 in. long have been made for special applications. A bare (uncoated) end of the electrode, standardized at a length of ¾ to 1½ in., is provided for making electrical contact through the electrode holder (see Fig. 1).

Classification of mild steel covered electrodes according to the system devised by the American Welding Society is generally used throughout industry. In this system, designations consist of the letter E (for "electrode") and four digits. The first two digits indicate minimum tensile strength, in 1000 psi, of deposited weld metal in the as-welded condition. The third digit indicates welding positions for which the electrode can be successfully used: E*xx*1*x* indicates all positions; E*xx*2*x*, flat welds and horizontal fillet welds only. The fourth digit indicates the type of covering and suitable current characteristics, as shown in Table 5. For example, E6011 is an electrode that deposits weld metal with a minimum tensile strength of 60,000 psi (first two digits); can be used for welds in all positions (third digit); has a high-cellulose, potassium covering and can be used either with alternating current or with reverse-polarity direct current (fourth digit).

Table 5. Coverings and Suitable Currents Indicated by Fourth Digit in AWS Classifications of Mild Steel Covered Arc Welding Electrodes

Fourth digit	Covering	Current(a)
0	High-cellulose, sodium(b)	Dcrp(b)
	High iron oxide(c)	Ac or dc(c) (d)
1	High-cellulose, potassium	Ac or dcrp
2	High-titania, sodium	Ac or dcsp
3	High-titania, potassium	Ac or dc(e)
4	Iron powder, titania	Ac or dc(e)
5	Low-hydrogen, sodium	Dcrp
6	Low-hydrogen, potassium	Ac or dcrp
7	Iron powder, iron oxide	Ac or dc(d)
8	Iron powder, low-hydrogen	Ac or dcrp

(a) Ac = alternating current; dc = direct current; dcrp = direct current, reverse polarity; dcsp = direct current, straight polarity. (b) When third digit is 1. (c) When third digit is 2. (d) Either polarity for flat welds; dcsp for horizontal fillet welds. (e) Either polarity.

Electrode Coverings. The composition of the electrode covering largely determines the performance of an electrode and the soundness of the weld. Table 6 lists 18 materials that are used in making electrode coverings, although there are more than 18 that can be used; 12 or more may be included in a specific covering. Each material is used for at least one, and often more than one, purpose. Table 6 gives typical compositions of electrode coverings for classes of electrodes used in welding low-carbon steel, and lists the primary and secondary functions of the constituents of the coverings.

The thickness of the covering varies from 10 to 55% of the total diameter of a covered electrode, depending mainly on the type of covering. Coverings are usually applied by extrusion of the flux onto the core wire.

Characteristics of Electrode Classes

E6010 and E6011 electrodes give a deep-penetrating, forceful, spray-type arc and are usable in all welding positions. They develop a low volume of slag that is easily removed. The deposits usually have good mechanical properties and are radiographically acceptable. The main constituent of the covering is cellulose, which decomposes during welding to provide a gas shield. The gases formed from the decomposition of cellulose and the high moisture content (up to 5%) of the electrodes produce the arc characteristics. The covering of E6011 electrodes contains potassium to assist in maintaining the arc when alternating current is used.

E6012 and E6013 electrodes provide a medium-penetrating arc. They yield a semiglobular to globular viscous slag that permits welding of joints with poor fit-up. The contour of horizontal fillet welds obtained by use of these electrodes varies from convex with E6012 electrodes to nearly flat with E6013 electrodes. Both types can be used for out-of-position welding, and most E6013 electrodes operate successfully in the vertical-down position.

The E6012 electrodes can be used at relatively high welding current, because the coverings contain only a small proportion of cellulose and a large proportion of refractory material.

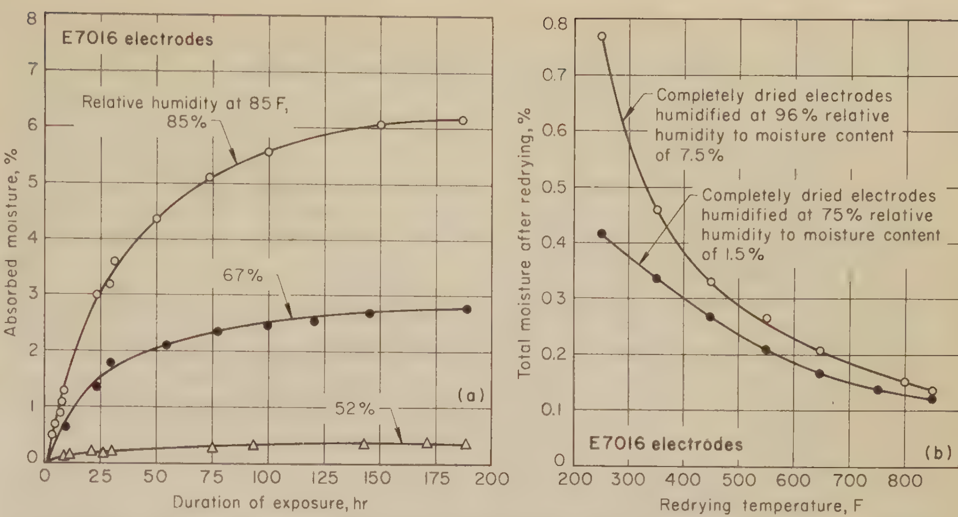
Coverings of E6013 electrodes generally contain more potassium than those of E6012 electrodes and thus give a quieter arc with less penetration. The high potassium content of the coverings of some E6013 electrodes permits the use of low open-circuit voltage. In small sizes, E6013 electrodes are most often used for welding of sheet metal.

E6020 electrodes provide a spray-type arc that has medium-to-deep penetration. They produce a heavy, honeycombed slag that is easily removed. Coverings for these electrodes consist mainly of the oxides of iron and manganese. Protection is provided by the volume of slag. The molten weld metal from these electrodes is too fluid for welding other than horizontal fillets or joints in the flat position. These electrodes have higher deposition rates than other conventional electrodes of equivalent sizes, and produce welds of equivalent strength and soundness.

Table 6. Typical Functions and Composition Ranges of Constituents of Coverings on Mild Steel Arc Welding Electrodes

Constituent of covering	Function of constituent: Primary	Secondary	Composition range, %, in covering on electrode of class: E6010, E6011	E6012, E6013	E6020	E6027	E7014	E7016	E7018	E7024	E7028
Cellulose	Shielding gas	...	25 to 40	2 to 12	1 to 5	0 to 5	2 to 6	...	...	1 to 5	...
Calcium carbonate	Shielding gas	Fluxing agent	...	0 to 5	0 to 5	0 to 5	0 to 5	15 to 30	15 to 30	0 to 5	0 to 5
Fluorspar	Slag former	Fluxing agent	...	...	...	...	...	15 to 30	15 to 30	...	5 to 10
Dolomite	Shielding gas	Fluxing agent	...	...	...	...	...	...	...	...	5 to 10
Titanium dioxide (rutile)	Slag former	Arc stabilizer	10 to 20	30 to 55	0 to 5	0 to 5	20 to 35	15 to 30	0 to 5	20 to 35	10 to 20
Potassium titanate	Arc stabilizer	Slag former	(a)	(a)	...	...	...	...	0 to 5	...	0 to 5
Feldspar	Slag former	Stabilizer	...	0 to 20	5 to 20	0 to 5	0 to 5	0 to 5	0 to 5	...	0 to 5
Mica	Extrusion	Stabilizer	...	0 to 15	0 to 10	...	0 to 5	...	...	0 to 5	...
Clay	Extrusion	Slag former	...	0 to 10	0 to 5	0 to 5	0 to 5	...	...	...	...
Silica	Slag former	...	...	...	5 to 20	...	...	...	...	...	...
Asbestos	Slag former	Extrusion	10 to 20	...	...	...	...	...	...	...	...
Manganese oxide	Slag former	Alloying	...	...	0 to 20	0 to 15	...	...	...	...	...
Iron oxide	Slag former	...	...	...	15 to 45	5 to 20	...	...	...	...	...
Iron powder	Deposition rate	Contact welding	...	...	...	40 to 55	25 to 40	...	25 to 40	40 to 55	40 to 55
Ferrosilicon	Deoxidizer	...	...	...	0 to 5	0 to 10	0 to 5	5 to 10	5 to 10	0 to 5	2 to 6
Ferromanganese	Alloying	Deoxidizer	5 to 10	5 to 10	5 to 20	5 to 15	5 to 10	2 to 6	2 to 6	5 to 10	2 to 6
Sodium silicate	Binder	Fluxing agent	20 to 30	5 to 10	5 to 15	5 to 10	0 to 10	0 to 5	0 to 5	0 to 10	0 to 5
Potassium silicate	Arc stabilizer	Binder	(a)	5 to 15(a)	0 to 5	0 to 5	5 to 10	5 to 10	5 to 10	0 to 10	0 to 5

(a) Used (in place of constituent on line above) in E6011 and E6013 electrodes to permit welding with alternating current



(a) Effect of relative humidity on moisture absorption of E7016 electrodes. (b) Redrying characteristics of E7016 electrodes. These values are typical; they will vary among different brands.

Fig. 9. Effects of humidity and redrying temperature on moisture in electrode coverings

Iron-Powder Electrodes. As shown in Table 6, the coverings on E6027, E7014, E7018, E7024 and E7028 electrodes contain iron powder in addition to the constituents present in coverings on several classes of conventional electrodes. Except for the iron powder, the constituents of E7014 and E7024 coverings resemble those of E6012 and E6013, and the constituents of E7018 and E7028 resemble those of E7016. In general, covering thickness increases as the content of iron powder increases. The iron powder and additional covering thickness permit higher welding currents and higher deposition rates than are possible with electrodes having coverings containing similar constituents but without iron powder. Thicker coverings also provide a deeper shield and permit the use of the drag technique in the flat position. In addition, the weld bead deposited in a horizontal fillet generally has a flatter contour when iron-powder electrodes are used.

When the covering of an electrode contains more than 40% iron powder, it is too thick to permit use of the electrode for vertical and overhead welding and for horizontal groove welds. Thus, the E6027, E7024 and E7028 electrodes, with 40 to 55% iron powder in the covering (Table 6), can be used only for flat-position welding and for horizontal fillet welds. (E6027 electrodes are also restricted as to welding position by the fluidity of the covering.)

E7016 electrodes have low-hydrogen coverings containing little or no hydrogen-bearing materials, such as cellulose, clays and asbestos. These electrodes are baked at a relatively high temperature (500 to 600 F) to minimize the retention of water from the silicate binder. Because of the low hydrogen content of the covering, the weld metal deposited is also low in hydrogen and is free of porosity. The carbon dioxide from the calcium carbonate, and the silicon fluoride (SiF_4) formed from the fluorspar in reaction with silicon dioxide, provide the shielding gas. The high proportions of titanium dioxide and of potassium silicate in the covering permit the use of E7016 electrodes with alternating current as well as reverse-polarity direct current.

E7015 electrodes are low-hydrogen electrodes used with reverse-polarity direct current. Although included in AWS A5.1-69, the E7015 electrodes are no longer generally manufactured.

Effect of Moisture in Electrode Coverings

It is often mistakenly considered that moisture is harmful in the coverings of all mild steel electrodes. Precautions are usually taken by fabricators to store electrodes in dry places, and this practice should be encouraged. However, redrying, which is often done after prolonged storage, can impair both quality and operation of electrodes with cellulose-type coverings, especially E6010 and E6011 electrodes.

Table 7 shows recommended moisture contents of coverings, and storage and redrying conditions for different classes of electrodes. Some brands of E6010 and E6011 electrodes will operate satisfactorily and produce satisfactory weld-metal deposits when the moisture content of the covering is above the recommended range. All other types of electrodes usually operate best when the moisture content is lowest.

Redrying temperature depends on the composition and thickness of the covering. Coverings containing organic material are usually redried at temperatures below the charring point (250 F), whereas inorganic coverings, such as the low-hydrogen types, are redried at temperatures up to 700 F. It is important that the drying procedure prescribed by the manufacturer be followed precisely for specific electrodes; otherwise, the electrodes may become unusable. Holding-oven temperatures shown in Table 7 should be maintained after redrying. Electrodes should not be removed from holding ovens for more than 1 or 2 hr before being used. Otherwise, redrying may be required.

Determination of Moisture Content. The moisture content of coverings on all except low-hydrogen electrodes can be determined by weighing an approximately 1-gram sample of the covering before and after redrying for 1 hr in an electric oven at 220 F. The weight loss calculated as percentage of predrying weight is the moisture content.

Moisture content for low-hydrogen electrodes is usually determined at temperatures between 1650 and 1800 F, using a special apparatus and technique as described in AWS A5.5-69.

E6010 and E6011 Electrodes. Manufacturers of E6010 and E6011 electrodes normally control moisture content so that it is between 3% and 5% for E6010 and between 2% and 4% for E6011. Therefore, a redrying practice that lowers the moisture content below the designed range is not recommended. E6010 and E6011 electrodes may perform satisfactorily even when the moisture content in the covering exceeds optimum values, but only if the covering does not blister during welding and does not interfere with operation of the electrode.

Ordinarily, the soundness of welds made with E6010 or E6011 electrodes is not impaired by excess moisture if the operation of the electrode remains satisfactory. When most brands of E6010 and E6011 electrodes are redried to a moisture content much below 2.0%, there is more weld spatter and increased probability of porosity in the weld metal. Arc control may also be impaired. The moisture content of E6010 electrodes can accidentally be decreased to values lower than the recommended level when a container is left open and electrodes are exposed to a hot, dry atmosphere.

Low-Hydrogen Coverings. The moisture content of low-hydrogen coverings (E7015, E7016, E7018 and E7028 electrodes) should be kept below the values in Table 7 (or, preferably, below 0.3%). If moisture content is much above these values, underbead cracking is likely. Low-hydrogen electrodes should not be allowed to remain in open boxes or bins for more than 1 or 2 hr.

A safe practice, followed by many fabricators, is to return all unused low-hydrogen electrodes after either a 2-hr exposure or a working shift to a redrying oven maintained at 250 to 350 F for at least 8 hr before reissuing them.

Figure 9(a) shows amounts of moisture absorbed by the covering on E7016 electrodes exposed for various periods of time to a humid condition (85% relative humidity at 85 F), a medium-

Table 7. Recommended Moisture Content of Coverings, and Storage and Redrying Conditions, for Mild Steel Covered Arc Welding Electrodes

Electrode class	Recommended moisture content of covering, %	Relative humidity, %, for storage at normal temperature of 80 ± 20 F	Temperature of holding oven, F	Redrying temperature, F (1 hr at temperature)
E6010	3.0 to 5.0	20 to 60	(Follow manufacturer's recommendation)	
E6011	2.0 to 4.0	20 to 60		
E6012, E6013, E6020	Less than 1	60 max	100 to 120	275 ± 25
E6027, E7014, E7024	Less than 0.5	60 max	100 to 120	275 ± 25
E7015, E7016	Less than 0.4	50 max	130 to 330	550 ± 50
E7018, E7028	Less than 0.6	50 max	130 to 330	650 ± 50

humid condition (67% relative humidity at 85 F), and a relatively dry condition (52% relative humidity at 85 F). Figure 9(b) shows the total percentages of moisture contained in coverings on E7016 electrodes after redrying the electrodes at about 250 to 850 F in a well-ventilated oven. Values shown in Fig. 9 are typical; they will vary considerably among different brands.

Times and temperatures required for restoring E7016 electrodes to their original usability after the coverings have absorbed the amount of moisture that causes underbead cracking differ for electrodes from different manufacturers. A procedure for one typical commercial brand of E7016 electrodes is as follows: Redry for approximately 1 hr in a well-ventilated oven by slowly increasing the temperature to 550 ± 50 F. Prolonged drying periods (weeks or months) at either lower or higher temperatures can cause the covering of some brands of E7016 electrodes to become brittle and crack.

Selection of Electrode Class

An all-purpose electrode for shielded metal-arc welding does not exist, although many types of covered electrodes overlap in adaptability to specific applications. To some degree, the class of electrode selected depends on whether alternating current or direct current is available for welding (see Table 5). Other factors in the selection of electrodes are:

1 Composition of the base metal
2 Position of welding
3 Fit-up
4 Service requirements of the welded joint
5 Penetration requirements
6 Cost of the welding operation
7 Skill of welding personnel.

Table 8. Penetration Obtained With Eleven Classes of Mild Steel Covered Electrodes

Electrode class	Penetration	Electrode class	Penetration
E6010	Deep	E6027	Medium
E6011	Deep	E7014	Medium
E6012	Medium	E7016	Medium
E6013	Less than E6012	E7018	Shallow
		E7024	Shallow
E6020	Medium(a)	E7028	Shallow

(a) Deep with high current

Composition of the base metal, which also influences the need for preheating and postheating operations, is the primary factor in electrode selection. All low-carbon ferritic steels can be welded with any class of mild steel electrodes, unless ambient temperature is low.

Steels having carbon content greater than about 0.35%, or tensile strength above 60,000 psi, are often welded using electrodes with low-hydrogen coverings or with iron-powder low-hydrogen coverings, to avoid the need for preheating and postheating (see the articles on Arc Welding of Hardenable Carbon Steels, page 187, and on Arc Welding of Alloy Steels, page 200).

Position of Welding. Welding in the vertical and overhead positions restricts the number of suitable classes of electrodes and generally decreases deposition rate. For this reason, most fabricators try to position workpieces so that welding will be in the flat or horizontal position (see "Positioning", on page 11). They can then use all-position electrodes at optimum deposition rate, or the higher-speed electrodes designed specifically for horizontal and flat-position welding.

Fit-up. Good fit-up of individual components of an assembly to be welded enables virtually any class of electrode to be used successfully. If there is a large root opening between components, special techniques or E6012 electrodes should be used.

Service Requirements. Electrodes with low-hydrogen coverings or iron-powder low-hydrogen coverings generally are used for applications in which welds must have high strength, good ductility, and good low-temperature impact strength. For welds that must pass radiographic inspection for soundness, general fabricating classes of electrodes, such as E6012, E6013, E7014 and E7024, are less useful. For best appearance of welds, E6020, E6027 and E7024 electrodes are often used.

Penetration requirements influence the selection of electrode class. The use of the wrong class of electrode can result in welds with penetration insufficient to provide adequate strength.

Table 8 compares the depths of penetration normally obtained with various classes of mild steel covered electrodes.

Cost of the welding operation is affected in two ways by the selection of electrode class. First, this selection influences the deposition rate, which often is the major factor in over-all cost of the welding operation. The second, and usually smaller, effect is the direct cost of the electrodes consumed.

For the electrodes listed in Table 10, deposition rate in ounces per hour is highest for the iron-powder electrode E7024 and the iron-powder low-hydrogen electrode E7028, and is much lower for welding with the remaining electrode classes, comparing equal diameters.

The iron-powder electrodes E6027 and E7024, which are relatively low in cost per pound of electrode and permit high deposition rates, often give the lowest over-all welding cost and provide weld quality adequate for many applications. For additional information on the relation of electrode selection to cost, see pages 21 and 22. Figure 34 compares electrode cost and arc time per inch of weld for E6020, E7018 and E7024 electrodes, and Table 15 and Example 8 give a complete cost breakdown for welding with E6013 and E7024 electrodes.

Welder Skill. Best results cannot be obtained in welding with a particular class of electrodes unless the welder is proficient enough in handling them. Flat-position electrodes, such as E6020, require less welder skill than the all-position electrodes, such as E6010. The low-hydrogen electrodes require greater welder proficiency than other types. Brief practice periods with a new type of electrode are always advisable.

Selection of Electrode Size

For many applications, obtaining the most economical operation depends as much on the selection of electrode size (diameter of the core wire) as on the selection of electrode class.

The principal considerations in selection of electrode size are joint design, thickness of the weld layer, welding position, permissible heat input, and the degree of welder skill. Table 9 shows typical ranges of welding current and welding speed at which several standard sizes of six classes of covered electrodes are used in making fillet and butt welds of various sizes in the flat,

Table 9. Typical Operating Conditions and Speeds for Various Sizes of Electrodes in Shielded Metal-Arc Fillet and Butt Welding in Different Positions

Electrode size, in.	Current, amp	Weld size, in.	Speed, ipm, for welding positions: Flat	Horizontal	Downhill, 30°	Vertical	Overhead
			E6011 Electrodes				
1/8	100 to 120	1/8	8 to 10	8 to 10	10 to 12	...	...
	110 to 120	1/8	...	...	...	7 to 8	7 to 8
5/32	120 to 140	5/32	8 to 10	8 to 10	10 to 12	...	...
	130 to 140	5/32	...	...	...	7 to 9	7 to 9
3/16	150 to 165	3/16	...	...	...	6 to 7	6 to 7
	160 to 175	3/16	9 to 11	9 to 11	11 to 13	...	...
			E6012 Electrodes				
1/8	120 to 140	1/8	13 to 15	12 to 14	14 to 18	4 to 5	4 to 5
5/32	150 to 170	1/8	15 to 16	14 to 16	13 to 17	...	...
	150 to 170	5/32	...	...	...	3 to 4	3 to 4
3/16	190 to 210	5/32	13 to 15	12 to 14	12 to 15	...	...
	190 to 210	3/16	...	...	...	3 to 4	3 to 4
	200 to 220	3/16	10 to 12	9 to 11	11 to 14	...	...
			E7014 Electrodes				
5/32	180 to 200	5/32	10 to 11	10 to 11	12 to 13	...	...
3/16	230 to 250	3/16	11 to 12	11 to 12	12 to 13	...	...
7/32	280 to 310	1/4	10 to 11	10 to 11	11 to 12	...	...
1/4	340 to 370	5/16	8 to 9	8 to 9	9 to 10	...	...
			E7018 Electrodes				
1/8	120 to 140	1/8	8 to 10	8 to 10	...	4 to 6	7 to 9
3/16	200 to 225	3/16	...	...	...	4 to 6	7 to 9
	220 to 240	5/32	13 to 14	12 to 13	...	...	...
	220 to 240	3/16	10 to 13	8 to 12	...	...	...
7/32	250 to 275	3/16	12 to 13	10 to 11	...	...	...
1/4	320 to 350	1/4	8 to 9	8 to 9	...	...	...
	320 to 350	5/16	6 to 7	6 to 7	...	...	...
			E7024 and E6027 Electrodes				
1/8	160 to 170	5/32	15 to 16	14 to 15	...	...	...
5/32	215 to 225	3/16	15 to 16	14 to 15	...	...	...
3/16	265 to 275	1/4	12 to 13	11 to 12	...	...	...
7/32	330 to 360	1/4	14 to 15	13 to 14	...	...	...
1/4	370 to 400	5/16	11 to 12	10 to 11	...	...	...

horizontal, 30° downhill, vertical and overhead welding positions.

The dimensions of a joint are established either by specifications or by welding procedures that have been qualified by test. The number of passes required to meet specifications depends largely on joint design, size of the electrode, thickness of the work metal, position of welding, and degree of skill of the welder.

All classes of covered electrodes are designed for multiple-pass welding. Electrode sizes suitable for use in different passes for some types of joints and welding positions are given below:

1 For pipe welds (or other single-welded joints) requiring good fusion at the root, a ⅛-in. or a 5⁄32-in. electrode is recommended for the first pass. For the remaining passes, 5⁄32-in. or 3⁄16-in. electrodes can be used in all welding positions; for welding in the flat position, electrodes that are 3⁄16-in. or larger can be used.
2 For flat-position welding of double-bevel or single-bevel joints that have a backing strip or can be back-gouged, a 3⁄16-in. electrode can be used for the first pass, and a 7⁄32-in. or larger electrode for the remainder.
3 For fillet welds in the flat position, 3⁄16, 7⁄32 or ¼-in. electrodes are satisfactory. Larger electrodes can be used if the work is thick enough to tolerate the additional heat.
4 For out-of-position fillet and butt welding, a 3⁄16-in. electrode is the largest that it is practical to use. Often the first pass is deposited with a 5⁄32-in. electrode.
5 The sizes of low-hydrogen electrodes generally used for vertical and overhead welding are ⅛ and 5⁄32 in.; electrodes for flat and horizontal welding are 3⁄16 in. or larger.

Electrode Deposition Rates and Properties of Welds

Deposition rate is the weight of metal deposited in a unit of arc time, and is generally expressed as pounds (or ounces) per hour. Table 10 shows typical deposition rates obtained in welding with covered electrodes of various sizes and classes. Table 10 also shows deposition efficiency and spatter loss, and lists the mechanical properties of weld metal obtained with some of the classes and sizes of electrodes. Under normal conditions, the data in Table 10 on electrode performance and weld properties can vary as much as ±7% because electrodes are obtained from different suppliers or are from different heats or lots from the same supplier, and because of difference in techniques of various welders.

For any specific class of covered electrode, deposition rates are primarily a function of the current setting at which the electrode is used. The type and size of the welding electrode and the welding position determine which power supply and current range will be used. Manufacturers of welding electrodes have recommended current ranges for each welding position in which their product may be used. (Some typical ranges are given in Table 9.)

Figure 10 shows the influence of current on the deposition rate, deposition efficiency (weight of deposited metal as a percentage of the net weight of electrodes consumed, exclusive of stubs), spatter loss, and weld-metal tensile strength and elongation, for ¼-in. E6011 electrodes. The shapes of the curves in Fig. 10 will vary for E6011 electrodes of sizes other than ¼ in., for different classes of electrodes, and for the same size and class of electrode obtained from different suppliers.

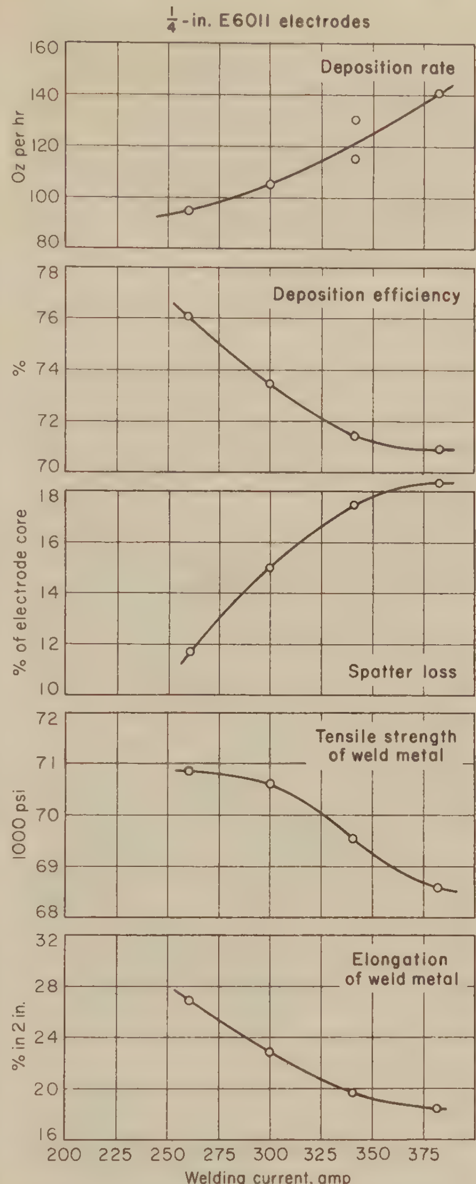


Fig. 10. Effect of current on deposition rate, deposition efficiency, spatter loss, and mechanical properties of weld metal, for ¼-in. E6011 electrodes

Arc Length

The end of an electrode must be close enough to the work to ensure that molten metal from the electrode will be transferred directly and accurately into the weld puddle. Arc length, the distance between the end of the electrode and the weld puddle, is a designed function of the electrode covering, but changes may be necessary under some welding conditions. In general, arc length should not exceed the diameter of the electrode core wire. Welders should deviate from this rule only on the basis of their skill and experience. Arc length is usually shorter for the types of electrodes that have thick coverings. Maintenance of arc length depends mainly on the skill of the welder — which, in turn, depends on his knowledge, visual perception, manual dexterity, and experience.

Arc length largely controls arc voltage and directly affects welding speed and efficiency. Shorter arcs allow an increase in current, which will increase rate of deposition and thus welding speed. When an arc is too long, heat is dissipated to the air, the stream of molten metal from the electrode to the work is scattered in the form of weld spatter, and deposition rate is reduced. In addition, susceptibility to arc blow, and porosity due to loss of shielding, increase as length of arc increases. In welding with direct current, the shortest possible arc is used, to minimize arc blow and contamination by the air.

Control of arc length in vertical and overhead welding demands greater attention from the welder and more skill than in welding in the flat position. In overhead welding, only certain types of electrodes can be used and the welder must adjust the arc length during deposition to retain control of the weld puddle.

For fillet welds, and for root passes in properly prepared butt welded pipe joints, the arc can easily be crowded into the joint for maximum speed and penetration.

The importance of controlling arc length is demonstrated in the example that follows.

Table 10. Typical Electrode Performance and Mechanical Properties of Weld Metal

Electrode class	Electrode size, in.	Current (ac), amp	Deposition rate (100% arc time), oz/hr	Deposition efficiency, %	Spatter loss, % of core wire	Properties of weld metal — Strength, psi — Tensile	Yield	Elongation in 2 in., %
E6011	3⁄16	200 max	88	76	16	70,000	60,000	25
	¼	300 max	112	72	...	...	...	...
E6012	3⁄16	225	66	68	14	79,000	66,000	20
	¼	380	120	78	16	71,000	58,000	15
	5⁄16	475	178	78	...	...	...	...
E6013	3⁄16	225	67	67	13	76,000	67,000	22
E6020	3⁄16	225	92	68	11	69,000	59,000	31
	¼	380	177	69	11	65,000	52,000	29
	5⁄16	450	215	69	9	63,000	50,000	28
E7014	3⁄16	260	87	68	...	74,000	68,000	23
	¼	340	119	69	...	73,000	67,000	25
E7016	3⁄16	225	63	70	6	87,000	75,000	29
E7018	3⁄16	240	83	69	...	80,000	67,000	29
E7024	3⁄16	270	134	68	...	90,000	80,000	22
	¼	360	186	69	...	89,000	77,000	22
	5⁄16	475	250	73	...	83,000	74,000	22
E7028	3⁄16	300	125	68	...	90,000	81,000	25
	¼	390	192	70	...	88,000	80,000	25

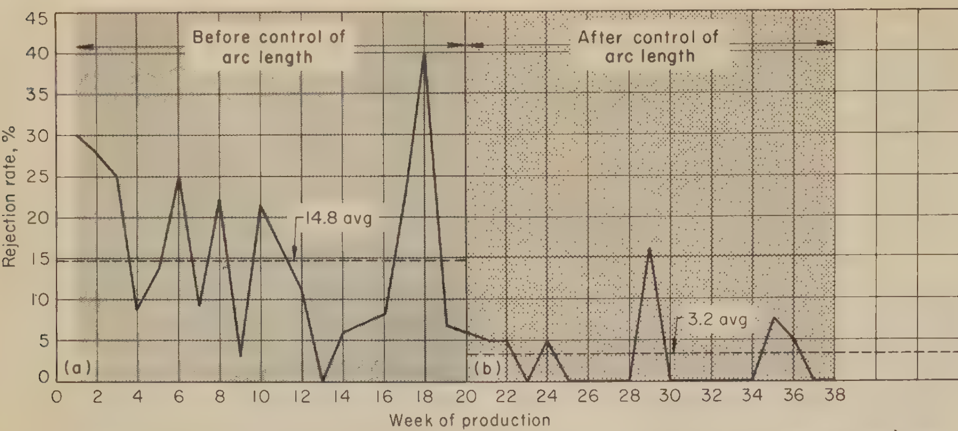


Fig. 11. Comparison of weekly rejection rates for porosity in welded pipe joints before and after control of arc length (Example 1)

Example 1. Control of Arc Length That Reduced Rejections for Porosity (Fig. 11)

Porosity in welded pipe joints was the cause of rejections that averaged 14.8%, with a high of 40%, over a 19-week period, as shown in Fig. 11(a). Investigation showed that the porosity resulted from failure to maintain a short arc length (for low voltage) in welding. When arc length was brought under control, average rejection rate over an 18-week period dropped to 3.2%, with no rejections in 12 of those weeks (Fig. 11b).

Arc Blow

An electric current flowing through the electrode, workpiece and ground cable sets up magnetic fields in a continuous series of circles perpendicular to the current path. When the fields around the workpiece or around the electrode are unbalanced, the arc bends away from the greater concentration of the magnetic field, and this deflection from its intended path is known as arc blow. Arc blow is encountered particularly when using direct current, because the induced magnetic fields are constant in direction. It occurs to only a minor degree with alternating current, because the induced magnetic field that builds up, collapses as soon as the current reverses.

Figure 12(a) shows magnetic fields around the electrode that result in forward blow (deflection in the direction of electrode travel) and backward blow (deflection opposite the direction of electrode travel). Sometimes deflection is to one side (because the concentration of magnetic flux is greater on one side of the arc than on the other), but usually deflection is in the direction of electrode travel or opposite to it.

Backward blow is encountered when welding toward the ground connection, toward the end of the joint, or into a corner. Forward blow is encountered when welding away from the ground connection or at the start of a joint. The conditions may become so severe that a satisfactory weld cannot be made because of incomplete fusion and excessive weld spatter. For instance, with electrode coverings containing large amounts of iron powder (such as 30%) or with other thick coverings, the large blanket of molten slag produced during welding can be troublesome. The difficulty arises because the forward fanning-out of the arc permits the heavy slag deposit in the crater to run under and ahead of the arc.

The forward blow at the start of a weld deposit is only momentary, because the magnetic field soon finds an easy path through the weld metal being deposited behind the arc. Because this following field is in the workpiece and the weld, a slight backward blow is created for the remainder of the weld.

At the finish end, the magnetic field ahead of the electrode is crowded and becomes a problem. As the end approaches, there is a corresponding increase in the backward blow, which may become severe.

The welding current passing through the work also causes the work to act as a conductor surrounded by a magnetic field. The circles of the magnetic field around the current path are in planes perpendicular to the workpiece, and are present between the electrode and the point at which the workpiece is grounded. This condition is most likely to occur in narrow plates.

In welding away from the ground connection, the magnetic field perpendicular to the workpiece is behind the electrode (Fig. 12b) and forward blow results. In welding toward the ground connection (Fig. 12c), the reverse is true and backward blow results.

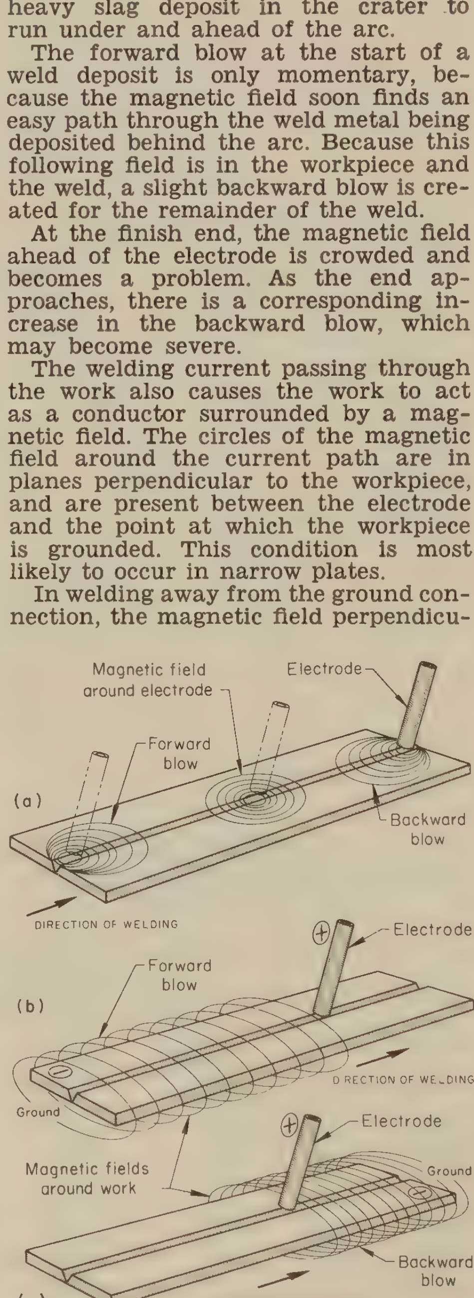


Fig. 12. Magnetic fields that result in forward or backward arc blow (a) *around the electrode;* (b) and (c) *around the work*

Corrective methods for use when severe arc blow is encountered are:

1 Change to alternating current.
2 Reduce welding current and keep arc length at the minimum.
3 Weld toward a heavy tack weld or toward an existing weld.
4 On long welds, use a backstep sequence.
5 Place the ground connection (*a*) as far as possible from the weld, (*b*) at the start of a weld and then weld toward a heavy tack weld, or (*c*) at the end of the weld.
6 Wrap the ground cable around the workpiece so that the current flows in a direction that will establish a magnetic field that will neutralize the magnetic field causing arc blow.

Electrode Holders

An electrode holder is a simple clamping device for holding the electrode, and is provided with an insulated handle for the welder's hand (see Fig. 1). The welding current is conveyed through the electrode holder to the electrode. The clamping device should be designed to hold the electrode securely in position and yet allow quick and easy change of electrodes, and also to provide good electrical contact.

Electrode holders vary from simple types that cost only a few dollars to the large, heavily insulated holders that are sometimes needed for welding with long duty cycles and high current. A typical general-purpose electrode holder is shown in Fig. 1.

It is generally advisable to use the lightest and simplest holder that will do the job; heavy, complex holders reduce the efficiency of the welder. Electrode holders usually are relatively inexpensive, and it is better to use the right holder for each application rather than to stretch the capabilities of another holder. Usually holders are selected according to current rating.

Welding in a confined space may require the use of a short-stub holder. With a short-stub holder, the electrode fits into a socket, and either the handle or the head of the holder is turned to operate the jaws that clamp the end of the electrode. A short holder enables the welder to operate in a confined space and to consume the electrode to a short stub.

The jaws of an electrode holder should be kept in good condition to ensure good electrical contact and to minimize heating in the holder. Poor contact can result in poor performance and low-quality welds. Electrode holders should never be cooled by immersing them in water.

For welding with alternating current, all components of an electrode holder should be nonmagnetic.

Ground Clamps

Ground clamps are devices for connecting the ground cable to the workpiece (see Fig. 1). A ground clamp must furnish a strong, positive connection, yet be quickly and readily movable from one part of the workpiece to another. It should be of rugged design.

Jigs, Fixtures and Positioners

The use of jigs, fixtures and positioners is usually desirable, for at least four reasons: (*a*) to minimize distortion caused by the heat of welding, (b) to permit welding in a more convenient position, (*c*) to increase welding efficiency and (*d*) to minimize fit-up problems.

With a welding jig or fixture, the components of a weldment can be assembled and held securely in proper relationship and with correct fit-up during positioning and during welding. The time required to assemble parts to be welded (setup and fit-up time) often is a large percentage of total fabricating time. If assembly follows a predetermined sequence of controlled fit-up and alignment conditions, welding efficiency will be increased.

For fabricating a single weldment or a few weldments of the same size and shape, temporary tooling can be used. For quantity production, it is economical to design and construct accurate, durable jigs or fixtures. If fixtures can pay for themselves in one year, the investment is generally considered sound. For producing a specific weldment in quantity, the use of duplicate jigs or fixtures makes it possible for a helper to fit together one assembly while the welder is welding another. Production is thus increased by adding only the cost of an extra fixture and a helper. The degree of increased production depends on the proportion of arc time to floor-to-floor time, and varies widely for different weldments.

Use of a specially designed fixture for assembling and tack welding 16 components of a large weldment is described in the example that follows.

Example 2. Benefits Provided by Use of a Fixture for Assembly and Tack Welding (Fig. 13)

The 16 major components of a low-carbon steel weldment were assembled in a specially designed fixture, as shown in Fig. 13. After being tack welded in the fixture, the assembly was removed from the fixture for final welding.

The fixture held each of the 16 components (some of which were welded subassemblies) in a predetermined position, and clamps kept them securely aligned. The sequence of assembly was unimportant, and highly skilled fitters were not required.

Although each component could have been tack welded as it was added to the assembly, it was more economical to complete the assembly in the fixture and then tack weld. Tack welding was done by the shielded metal-arc process, using a 5⁄32-in. E6010 electrode. Each component was tacked at its extreme corners and, wherever possible, with ½-in. tack welds on 7-in. centers. With this amount of tack welding, the assembly had enough strength and rigidity to be removed from the fixture, transported, and positioned for welding. The following benefits were provided by the use of fixtures:

1 The components were fitted and tack welded in 2.25 man-hr; free fitting had required 5.25 man-hr.
2 Less fitting skill was required and the skilled personnel were consequently available to handle more complex fitting.
3 Less time was required to train the fitters.
4 Weldments were more uniform.
5 The completed weldments required less straightening and grinding; less time for final assembly, because fewer tailoring operations were required; and less preparation time for painting, because outside appearance was more uniform.

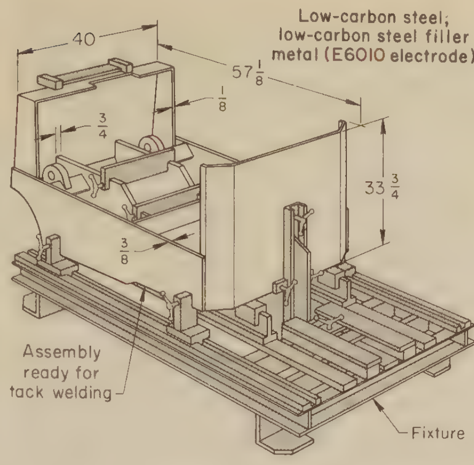


Fig. 13. Sixteen-component assembly mounted in a fixture and ready for tack welding (Example 2)

Desirable features for fixture design include the following:

1 Whenever possible, the fixture should be designed so that all joints in an assembly are convenient for welding without removing the assembly from the fixture. Slots, or other means of access to joints on the reverse side of the weldment, should be provided.
2 The fixture should be strong and light, but rigid enough to ensure accurate alignment.
3 The fixture should permit quick and easy positioning (by one hand, if possible). Thus, balancing of the fixture may be necessary.
4 The use of light alloys for moving parts reduces weight. Air or electric motors should be used for revolving, and air or hydraulic rams or racks for tilting the fixtured assembly.
5 For maximum utility and minimum cost, the accuracy and complexity of a fixture should be no greater than required. Welded steel construction is usually best.
6 The fixture should permit location and clamping of components in position so that assembly, tacking and welding can be done in one fixture.
7 The fixture should permit freedom of movement in one plane, to avoid residual stress in the completed weldment. Design should permit heat distention to release, rather than bind, the assembly being welded.
8 Floating rather than rigid anchoring is recommended.

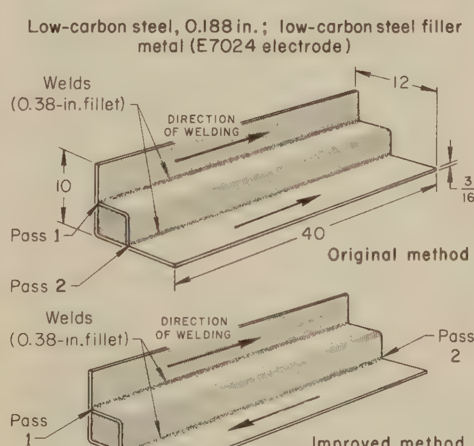


Fig. 14. Weldment for which reversal of pass direction eliminated the need for clamping to keep distortion within acceptable limits (Example 3)

9 Fixtures should be kept cool enough to handle; air, water, fins or insulated handles can be used.
10 To facilitate shop flow, jigs or fixtures can be mounted on wheels, or used in conjunction with floor-mounted or overhead conveyors. Alternatively, they may be located in a production line so that the work can be moved directly to and from them.
11 Indexing arrangements are helpful in providing accurate, quick positioning of work.
12 Clamps must operate quickly. Screws and moving parts should be protected against weld spatter. Fusion to a fixture or to clamps can be avoided by the use of slots or copper backing. If possible, clamps and locating devices should be integral with, and hinged to, the fixture.
13 Use of nuts and bolts, wrenches, C-clamps, wedges and hammers, and hand screws should be minimum. Use of eccentrics and cams, cranks, pinions and racks, air or hydraulic rams, solenoids, or magnetic clamps is preferred.
14 The fixture must be designed to permit quick and easy removal of the weldment.

Technique To Minimize Fixturing. Sometimes the need for fixturing or clamping to prevent excessive distortion can be minimized or eliminated by a change in welding technique. The change in welding technique need not be complicated and may consist merely of a change in welding direction, as in the application described in the example that follows.

Example 3. Change in Pass Direction That Minimized Distortion Without Need for Clamping (Fig. 14)

The 3⁄16-in.-thick low-carbon steel weldment shown in Fig. 14 was initially produced by welding both joints in the same direction (upper view in Fig. 14). With this technique it was necessary to clamp the assembly securely to a table during welding and cooling, to keep distortion within acceptable limits.

When the two joints were welded in opposite directions (lower view in Fig. 14), distortion was within acceptable limits without the need for clamping.

The weldment was made by first tack welding, using a 5⁄32-in. E7014 electrode and 200-amp current, and then depositing the 0.38-in. fillet welds with ¼-in. E7024 electrodes at 405 amp.

Positioning is sometimes essential simply to make joints accessible, because assemblies usually require more than one weld. The main object of positioning, however, is to increase welding speed by putting the joint in a flat (or at least more favorable) position. Such increases in speed are often considerable. Changing from a vertical or overhead position to a flat position can increase welding speed by up to 400%. Flat-position welding also improves weld quality, because it increases the ease of welding.

In flat-position welding, deposition is assisted by gravity. Electrodes with coverings containing iron powder, which have a deposition rate up to 50% greater than that of other types of electrodes having the same core-wire size, can be used at maximum efficiency in welding in the flat position.

Positioners. Devices for positioning can be made readily. Because of the many different types of positioners available, manual positioning in production welding is seldom justified. The headstock-and-tailstock type of

positioner (see Fig. 15) is available in many sizes and is widely used for positioning large, bulky assemblies. This type of positioner is extremely flexible, because the headstock and the tailstock are separate units.

Figure 16 shows a positioner on which a workpiece can be rotated and tilted, by the use of either manual or power drives. It is available in sizes ranging from small bench models to large floor models that have capacities exceeding 100 tons. The general type of positioner shown in Fig. 16 can be modified in various ways as needed. The view at left in Fig. 17 shows a rotary positioner that can be used for welding with either manually or mechanically held electrode holders. In the middle view in Fig. 17 a workpiece is in position on it for welding of one side; in the view at right the workpiece has been inverted on the positioner for welding of the opposite side.

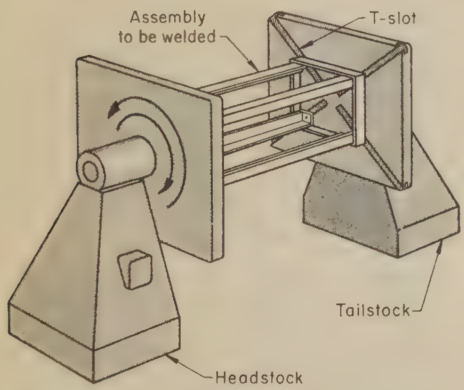


Fig. 15. Headstock-and-tailstock positioner that holds and rotates bulky assemblies

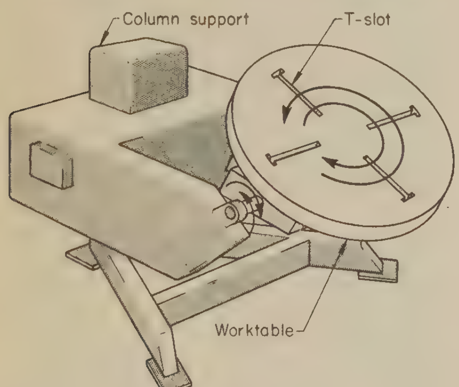


Fig. 16. Positioner that rotates and tilts workpieces

For welding cylindrical workpieces, such as tanks, a roll-type positioner (Fig. 18) is advantageous. The speed of the drive rolls can be regulated as needed, and rotation can be constant or intermittent, and in either direction.

Workpieces often are rotated in a lathe or in a specially designed mechanism that permits welding in the most efficient position. Positioning devices discussed and illustrated in the articles on Gas Metal-Arc Welding and Gas Tungsten-Arc Welding are also applicable to shielded metal-arc welding.

Accessory Equipment

Oxyacetylene torches are often used to bevel edges before welding, and when fitted with special gouging tips (see page 299 in Volume 4 of this Handbook), are used to gouge out defective welds in preparation for repair welding. Gouging may also be done with a carbon-graphite electrode and compressed air (see "Air Carbon-Arc Cutting" on page 301 in Volume 4).

Hammers in assorted sizes and a pry bar are needed in many applications to obtain the desired fit-up.

Heat-sensitive crayons or pastes are used to determine preheat and interpass temperatures.

Deslagging chisels or hammers are needed for cleaning the welds between passes. Wire brushes are normally used for cleaning the surfaces of the joint before welding and for cleaning the layers of welds. Deslagging hammers and wire brushes are either manual or power operated. Rotary grinders are also needed to grind out defects for repair welding.

Striking, Maintaining and Breaking an Arc

An arc is struck by touching the work with the electrode and then quickly withdrawing the electrode to normal arc length (see the section on Arc Length, on page 9). When contact is made, the electrode tends to "freeze", or stick, to the workpiece. Often a lateral scraping or scratching motion similar to that in striking a match is necessary to prevent sticking.

The method of restriking an arc varies with electrode type. Generally, the projecting covering on the electrode tip (shown as "Cup" in section A-A in Fig. 1) becomes conductive during use and assists in restriking and maintaining the arc, particularly when the covering contains iron powder. To permit restriking when electrodes such as E6020, low-hydrogen electrodes, and stainless steel electrodes are used, the projecting covering may have to be broken by tapping the tip to expose the core wire.

The arc is maintained by a uniform movement of the electrode toward the work to compensate progressively for the portion of the electrode that has been melted and deposited in the weld puddle. At the same time, the electrode is also advanced progressively in the direction of welding.

Various procedures are employed to break the arc at the end of a weld. In one procedure, the electrode is drawn to the end of the joint, making a somewhat lighter deposit, the direction of electrode travel is reversed, and then the electrode is withdrawn. In another procedure, the electrode is held stationary long enough to fill the crater and then is withdrawn.

In welding long joints, when electrodes are changed and welding is to be continued from the crater, the arc is shortened, and then is stopped by quickly moving the electrode sideways out of the crater. When the arc is re-established in the crater, it should be struck at the forward, or cold, end of the crater, moved backward over the crater until the weld is reached, and then forward to continue the weld. This procedure is especially beneficial in eliminating "starting porosity". For electrodes that deposit heavy slag, if the slag has cooled below a red heat, it is necessary to remove the slag before restriking the arc. With this procedure, the crater is filled and porosity and trapping of slag are avoided. It is particularly important that this procedure be used in welding with low-hydrogen electrodes.

Electrode Angle and Manipulation

The angular position of the electrode in relation to the weld influences the ease with which filler metal is deposited, uniformity of fusion, and weld contour. Correct positioning of the electrode also ensures freedom from undercutting and slag inclusions.

As shown in the top view in Fig. 19, the lead angle of the electrode is the angle that the electrode makes in advance of a line perpendicular to the weld axis at the point of welding, taken in a longitudinal plane; the work angle is the angle that the electrode makes with a line perpendicular to the weld axis at the point of welding, taken in a transverse plane. Figure 19 shows typical lead and work angles for flat-position welding and for horizontal fillet welding.

Techniques for specific welding positions vary considerably among welders, and much practice is required before a welder can become proficient at making good welds. Regardless of the technique used, the goal is a sound weld. Two fundamental rules are: (*a*) radical motions of the electrode should not be used, because entrapment of slag in the weld must be avoided; and (*b*) the arc must not be broken if the electrode is "hopped" from one side of the puddle to the other.

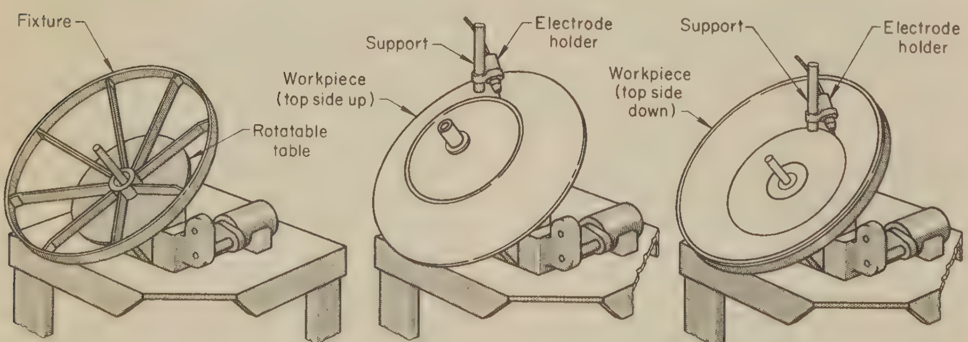


Fig. 17. Rotary positioner that can be used for welding two sides of a workpiece, with either a manually held or (as shown) a mechanically held electrode holder

Slag is usually more fluid than weld metal. Therefore, some electrodes, particularly the electrodes that have heavy coverings and produce a thick slag blanket on the weld, can be used only in the flat position. Obviously a welder cannot cope with slag that runs ahead of the weld or that falls off the weld during out-of-position welding. Even all-position electrodes require specific techniques for out-of-position welding. These techniques, which enable the welder to keep the weld metal where desired, are generally acquired only by training and experience.

It is frequently necessary to change the technique when the type of electrode is changed, even though both electrodes are all-position electrodes. For instance, an E6010 electrode requires a technique different from that for an E7018 electrode.

In welding in the vertical position, different techniques of electrode manipulation may be used for different passes. For a vertical joint with a root opening, the root pass may be made by advancing the electrode with a slight up-and-down motion or a slight inverted-T motion, and the next pass, or passes, may be made with a weaving motion. With the inverted-T technique, the electrode is first raised slightly above the weld puddle (not enough to break the arc), then dropped straight down to (but not touching) the puddle, and then moved from side to side so that metal is tied to both sides of the joint. With the weaving technique, often required in out-of-position welding, the advancing electrode is moved from side to side of the weld puddle and, as each side is alternately reached, is raised slightly and then lowered to impinge on the side of the puddle.

Electrode Clearance. The joint to be welded should provide clearance between the parts joined and the electrode. Figure 20 shows limiting dimensions for clearance that will avoid interference and provide visibility to the bottom or end of the joint.

Techniques for Limited Accessibility. In shielded metal-arc welding, a long, small-diameter electrode can be used to make a weld in spaces too confined to permit the use of an electrode holder of the type required for gas metal-arc or gas tungsten-arc welding. Where weld accessibility is extremely limited, it may be necessary to bend the electrode slightly in order to reach the weld area. When this is done, the electrode covering must remain intact, to provide protection for the arc and the weld puddle. Not all electrodes will bend and still retain an intact covering. Class E6013 electrodes will usually bend satisfactorily without damage to the covering, but because of variations in electrode manufacture, not all electrodes of this class will bend. Correct moisture content is extremely important for satisfactory bending; if a covering is too dry, it will crack and spall when bent. Heating the electrode by shorting it out may help in bending.

Effect of Welding Speed

Welding speed is the rate of travel of the electrode in relation to the workpiece, regardless of which is moving. Optimum speed depends on the melting rate of the electrode, type of current, closeness of fit-up (see the section on Fit-up, on page 14), composition of the metal being welded, type of electrode being used, welding position, and welding technique.

Welding speed must be high enough to permit the arc to lead the puddle slightly. Increasing welding speed while maintaining constant arc voltage (arc length) and constant current will reduce the width of the weld bead and increase penetration, until an optimum speed is reached at which penetration will be maximum. Speeds greater than the optimum may result in decreased penetration, poor appearance, undercutting at the edges of the weld, tight slag, and porosity. The optimum speed is usually the highest speed at which weld quality, slag removal, bead size, and surface appearance of the weld are acceptable. The welding speed has a major influence on extending or restricting the limits of the heat-affected zone. Thus, welding speed affects the structure and hardness of the weld and of the heat-affected zone.

If a smaller weld bead is produced by use of a higher speed, with no other change, heat input per unit of weld seam length will be less. Faster cooling and, consequently, greater hardening will result. If the same size of weld bead is produced by the use of a higher current and a higher speed, heat input per unit of length will be the same but the rate of heat input and the rate of cooling will be higher. Hardening, therefore, will be more pronounced.

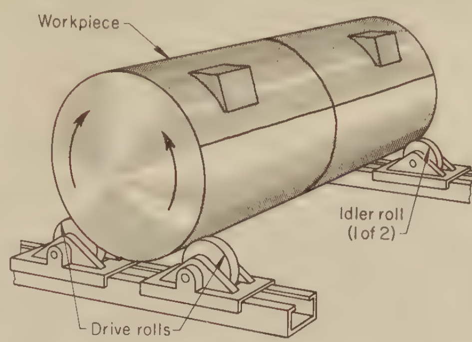


Fig. 18. Roll-type positioner for use in welding of cylindrical workpieces

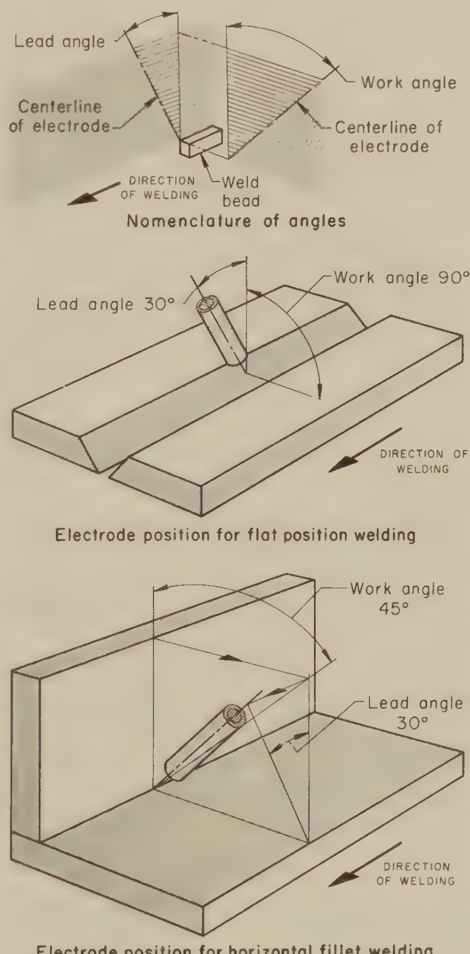


Fig. 19. Typical lead and work angles of electrodes for flat-position welding and horizontal fillet welding

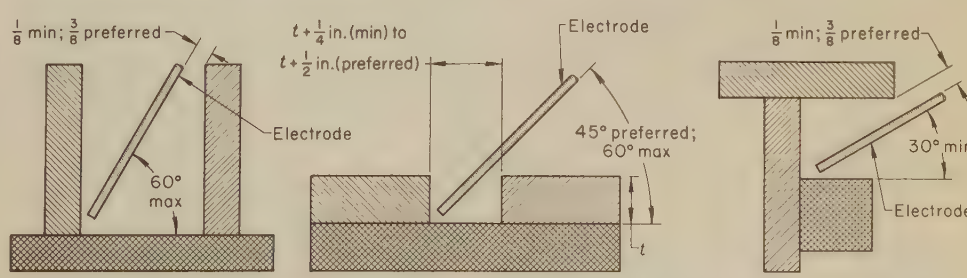


Fig. 20. Typical electrode clearances used to avoid interference and provide welder visibility

Welding Procedures

After a joint design has been selected and the edges of the members have been prepared, the first step in welding is to place the parts in position and to adjust them for optimum fit-up. Tack welds are frequently used to hold the fixed positions. For welds in joints that require more than a single pass, welding is initiated by depositing a narrow bead at the bottom of the joint. Welding then proceeds by depositing consecutive beads over the original bead until the desired dimension of the weld is obtained. The weld should be cleaned (deslagged) following each pass in multiple-pass welding.

Procedures vary considerably, depending on joint design, position of joint, thickness of sections being welded, and variation of thickness among sections being welded. These variables and the procedures that deal with them are discussed in the sections that follow.

Joint Design

Joint design (shape and dimensions) is determined by the design of the workpiece, metallurgical considerations, and established codes or specifications.

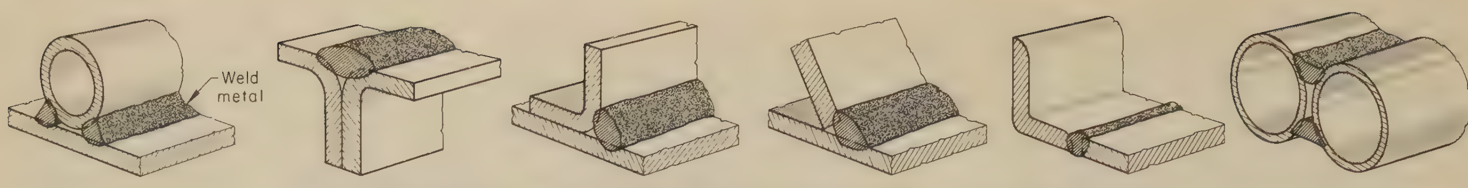


Fig. 21. Joints that have natural grooves and thus need little or no edge preparation

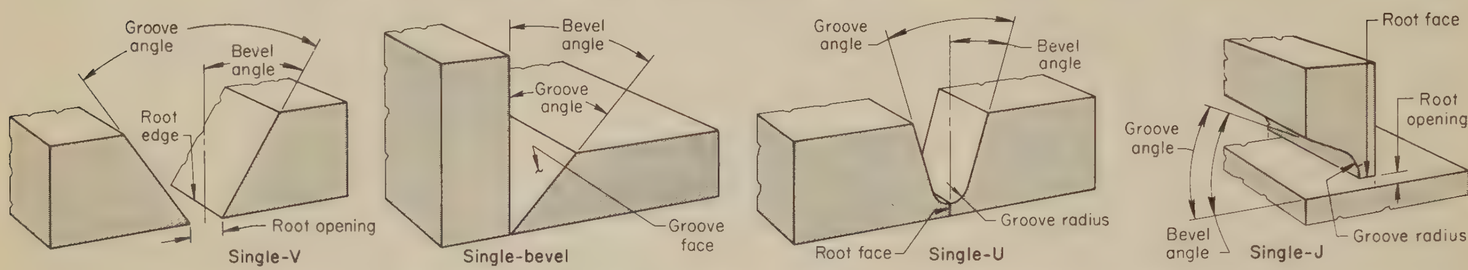


Fig. 22. Nomenclature for four standard types of single-groove joints frequently used in shielded metal-arc welding

Edge Preparation. Joints for square-groove and for fillet welding are prepared by simply squaring off the edge to be welded on each member, if the as-received edge is not suitable. Edge preparation for bevel, V, U, J and combination grooves is more complex.

Methods most often used for edge preparation are machining, chipping, shearing, grinding, gas cutting, gas gouging, and air carbon-arc gouging.

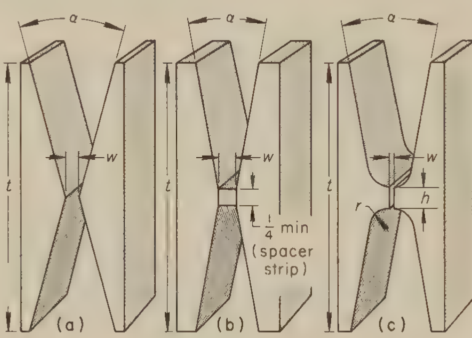
Joints in metal up to 3⁄16 or ¼ in. thick seldom require beveling for complete penetration. Partial-penetration welds can be made in work metal up to ½ in. thick without beveling.

Some joints have natural weld grooves (Fig. 21) and require minimum or no edge preparation.

Standard Groove Types. Nomenclature for angles, faces, radii and root openings in several standard types of groove joints is given in Fig. 22. Recommended proportions and dimensions for standard joints are given in "Recommended Proportions of Grooves for Arc Welding", pages 148 to 150.

Single-bevel grooves and V-grooves are the types most often used, because they are easily prepared by gas cutting. Edges of U-grooves can be prepared by gas cutting, using special tips and techniques, or by machining, which produces more uniform grooves.

U-grooves generally require less weld metal than V-grooves, but the use of spacer strips in V-grooves (see Fig. 23b) sometimes results in the same saving of weld metal, in addition to providing the economy of gas cutting.



Joint	t, in.	α, deg	w, in.	r, in.	h, in.
(a)	4 to 6	30	3⁄16	...	...
(b)	4 to 6	20	¼	...	...
	Over 6	10	½	...	...
(c)	4 to 6	20	0-1⁄16	3⁄16	¼-5⁄16
	Over 6	10	0-1⁄16	5⁄16	¼-5⁄16

Fig. 23. Shapes and dimensions of three joints for groove welding of sections over 4 in. thick

A U-groove, which has a generously rounded bottom, permits the use of larger electrodes for the first pass than can be used with V-grooves, which have a sharp or only slightly rounded bottom. There is, however, little or no difference between the welding speeds obtained for U-grooves and V-grooves up to 1 in. deep.

Single-bevel and -J grooves are well suited for T-joints and corner joints. Single-V, -U and -bevel grooves are the usual edge preparation for butt joints 3⁄16 or ¼ in. to about ¾ in. thick.

For metal ¾ in. thick or more, double-bevel, double-V, double-J and double-U grooves are recommended if welding from both sides is possible. Joints with these grooves produce less distortion of the welded parts and reduce the amount of weld metal required for a given thickness. Three joint designs for groove welding of sections over 4 in. thick are shown in Fig. 23. The joints shown in Fig. 23(b) and (c) are specially designed so that the groove angle can be reduced. A reduction in the groove angle reduces the amount of weld metal required to fill the joint and minimizes cracking in thick sections.

Groove angles of 45° to 60° are used for thinner sections requiring grooves, but are not satisfactory for thick sections because excessive amounts of weld metal are required to fill such large grooves. Large savings can be realized by keeping the amount of filler metal and the arc time to a minimum.

Weld Location

Welds should preferably be located away from points of maximum stress. Figure 24 shows two sets of examples of poorly and properly placed welds for different directions of loading. The poorly placed welds result in stress concentrations in unwelded regions of the joints.

On double-welded lap joints, the overlap should be small enough to prevent buckling or separation.

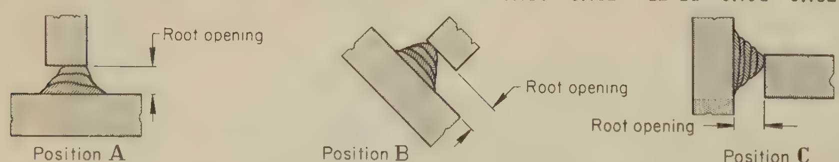
Fit-up

Poor fit-up increases welding time, and often is the cause of unsound welds. In the welding of sheet steel 0.060 in. thick (the minimum practical thickness for shielded metal-arc welding), good fit-up is mandatory; if fit-up is poor, unsound welds (often because of burn-through) will result. Some desirable and undesirable fit-ups in joints of which the components are 0.060-in.-thick sheet are shown in Fig. 25.

Table 11 shows the arc time required for bridging root openings of 3⁄16 to ½ in., with the use of 3⁄16-in. E7018 elec-

Table 11. Arc Time Required for Bridging Root Openings of Various Sizes in Welding Low-Carbon Steel With 3⁄16-In. E7018 Electrodes and the Stringer-Bead Technique in Three Positions(a)

Root opening, in.	Position A: Number of passes	Position A: Arc time, min/in. of weld, for melting rate, ipm, of: 9.0	9.5	10.0	Position B: Number of passes	Position B: Arc time, min/in. of weld, for melting rate, ipm, of: 9.0	9.5	10.0	Position C: Number of passes	Position C: Arc time, min/in. of weld, for melting rate, ipm, of: 9.0	9.5	10.0
3⁄16	1	0.202	0.191	0.182	1	0.214	0.202	0.192	1	0.227	0.215	0.204
¼	2-3	0.348	0.330	0.313	2-4	0.354	0.336	0.319	3-5	0.368	0.349	0.331
5⁄16	3-4	0.474	0.449	0.427	4-5	0.482	0.456	0.434	5-7	0.496	0.470	0.447
⅜	4-6	0.581	0.550	0.523	5-7	0.594	0.563	0.535	7-9	0.608	0.576	0.547
7⁄16	5-7	0.670	0.635	0.603	8-10	0.696	0.659	0.626	10-12	0.711	0.674	0.640
½	6-8	0.735	0.697	0.662	10-12	0.778	0.737	0.701	12-14	0.794	0.752	0.714



(a) Arc times shown represent only the time required for bridging the root openings. Total arc time would include the time required for completing the fillet weld.

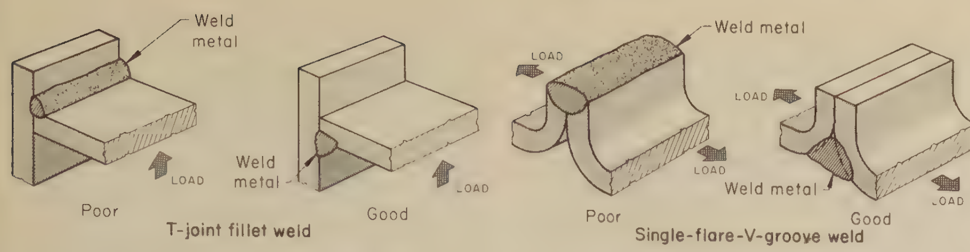


Fig. 24. Poor and good locations of welds in relation to direction of loads

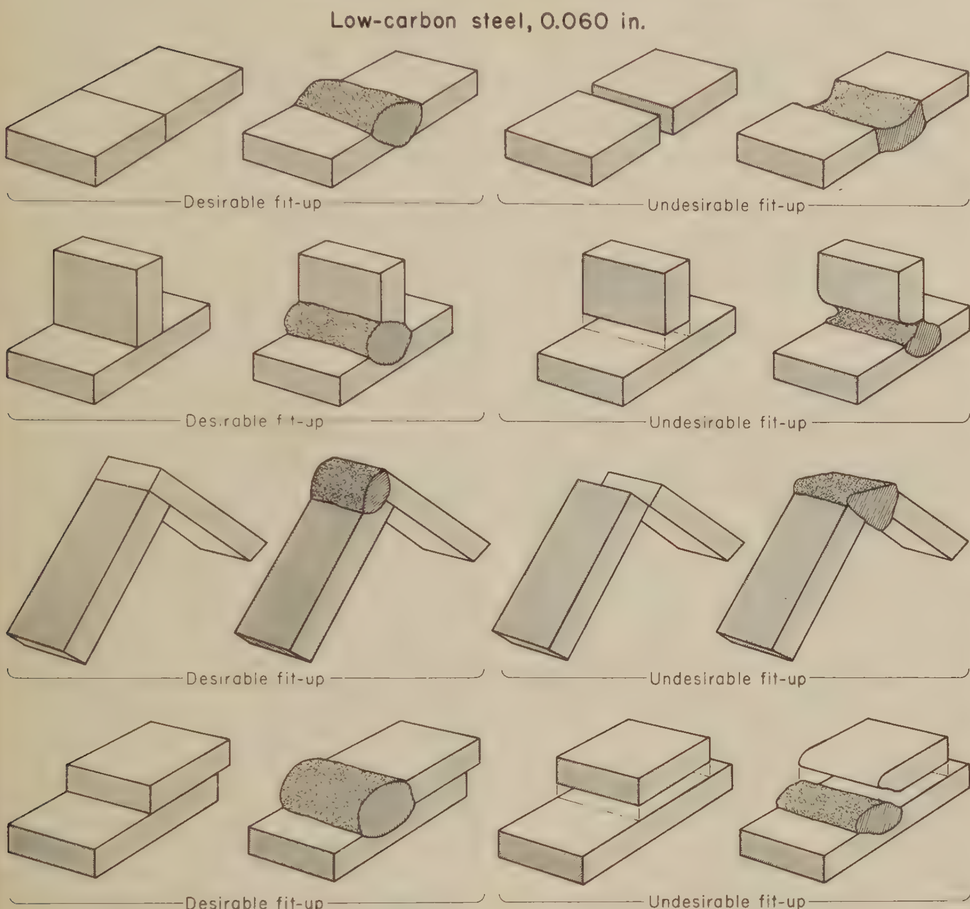


Fig. 25. Effect of desirable and undesirable fit-up on soundness of welds in joints between steel sheets 0.060 in. thick. Poor fit-up of joints in the top three rows may also result in complete melt-through.

trodes, in welding low-carbon steel in three different welding positions.

Figure 26 shows the effect of size of root opening on the speed with which butt joints can be welded in low-carbon steel plate of various thicknesses. These data, for welding of square-groove or single-V-groove butt joints from both sides in the flat position, show that for 1/4-in.-thick plate, a joint with a 1/32-in. root opening can be welded nearly three times as fast as the same joint with a 3/16-in. root opening. A 1/32-in. root opening is the minimum shown in Fig. 26, but a further reduction, to 1/64 in., prevents angular distortion and weld cracking in some applications.

Size of root opening has a similar effect on welding time for fillet welds. A 7/16-in. fillet weld in the flat position can be made at 12 in. per minute with a 1/32-in. root opening, but at only 8 in. per minute with an 1/8-in. root opening; and a root opening of 3/16 in. will require multiple-pass welding and a speed of only about 3 in. per minute.

For unusually large root openings, an overlay may be deposited on the joint faces to reduce the root opening.

Fillet Welds

Fillet welds as large as 1 in. require six to eight passes and usually have poor appearance. Where strength greater than a 3/8-in. fillet weld can provide is required, edge preparation such as a 1/4-in. bevel in the joint should be considered before enlarging the fillet size. Welding conditions for various sizes of fillet welds are given in Table 12.

Single-Pass Fillet Welds. The maximum size of sound fillet weld that can be made in a single pass depends on the position of welding, electrode size, electrode type, amperage, and work-metal thickness. Attempts to make fillet welds that are too large for one pass can result in undercutting, unequal legs, lack of penetration, and slag entrapment. The largest size of single-pass fillet weld is 3/8 in. in the flat position, 5/16 in. in the horizontal and overhead positions, and 1/2 in. in the vertical position. Typical sizes of various classes of electrodes for five sizes of single-pass horizontal fillet welds are given in Table 13.

Table 12. Conditions for Fillet Welding in Flat and Horizontal Positions With E7018 Electrodes(a)

Fillet size, in.	Pass No.	Electrode size, in.	Current, amp: Range	Current, amp: Optimum	Melting rate, in./min
Welding in Flat Position					
1/8-5/32	1	1/8	120-160	140	...
1/8-3/16	1	5/32	150-220	170	...
5/32-3/16	1	3/16	240-300	260	11.60
3/16-5/16	1	7/32	280-350	300	...
1/4-3/8	1	1/4	320-400	350	9.54
3/8	1(b)	5/16	420-540	460	...
7/16-5/8	1	7/32	280-350	300	...
	1(c)	1/4	320-400	350	9.54
	2(b)	5/16	420-540	460	...
11/16-3/4	1	7/32	280-350	300	...
	1(c)	1/4	320-400	350	9.54
	2	5/16	420-540	460	...
	3,4(b)	5/16	420-540	460	...
Welding in Horizontal Position					
1/8-5/32	1	1/8	120-160	140	...
1/8-3/16	1	5/32	150-220	170	...
5/32-1/4	1	3/16	240-300	260	11.60
3/16-5/16	1	7/32	280-350	300	...
1/4-5/16	1	1/4	320-400	350	9.54
3/8-7/16	1	7/32	280-350	300	...
	1(c)	1/4	320-400	350	9.54
	2	1/4	320-400	350	9.54
1/2-5/8	1	7/32	280-350	300	9.54
	1(c)	1/4	320-400	350	9.54
	2, 3	1/4	320-400	350	9.54
11/16-3/4	1	7/32	280-350	300	...
	1(c)	1/4	320-400	350	9.54
	2-6	1/4	320-400	350	9.54

(a) For welding with alternating current or reverse-polarity direct current, using the stringer-bead technique (except where use of weaving is footnoted to pass number), chipping for multiple-pass welds, and using small-diameter electrodes to tie-in ends and corners of joints. (b) Using weaving technique. (c) Alternative first pass.

Table 13. Classes and Sizes of Electrodes for Single-Pass, Horizontal Fillet Welds

Electrode class	Electrode size, in., for fillet size, in., of: 1/8	3/16	1/4	5/16	3/8(a)
E6012, 6013 ...	5/32	3/16	1/4	1/4	1/4
E7014	1/8	5/32	7/32	1/4	1/4
E7018	1/8	5/32	3/16, 7/32	1/4	1/4
E7024	1/8	5/32	3/16, 7/32	7/32	...

(a) Usually made in two passes; a great deal of operator skill is required for making a 3/8-in. fillet weld in one pass.

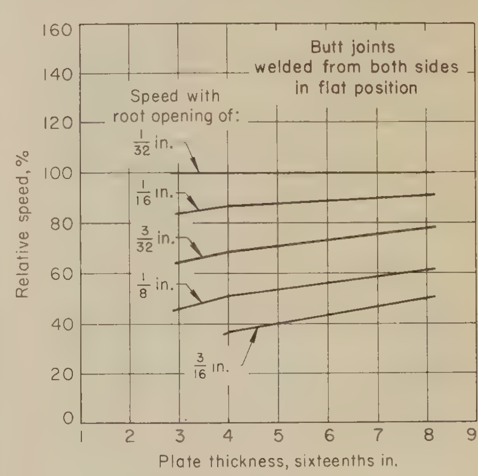


Fig. 26. Effect of size of root opening on speed of flat-position welding of square-groove and single-V-groove butt joints in low-carbon steel plate of various thicknesses

Multiple-Pass Fillet Welds. For larger fillets that require multiple-pass welding, horizontal fillets usually require more passes than flat fillets.

Effect of Work-Metal Thickness. For a given thickness of work metal, a fillet weld should be no larger than is required for adequate strength. Needlessly large welds add to cost by increasing deposition time and wasting metal. Minimum sizes of fillet welds for adequate strength, and for avoiding cracking due to joint stresses during cooling, are:

Thickness of thicker member, in.	Minimum size of fillet weld, in.
Up to ¼	⅛
¼ to ½	3⁄16
½ to ¾	¼
¾ to 1½	5⁄16
1½ to 2¼	⅜
2¼ to 6	½
Over 6	⅝

Intermittent Welds. An intermittent fillet weld, one of broken continuity, is often used when the strength of a continuous fillet weld of minimum size exceeds requirements (unless a continuous weld is required for appearance or because the welded joint must be leakproof or weatherproof). For adequate strength, the minimum length of an intermittent weld should be at least four times the size of the fillet, and not less than 1½ in.

Maximum center-to-center spacing of intermittent welds should not exceed 16 times the thickness of the thinner member of joints that will be loaded in compression, or 32 times the thickness of the thinner member of joints to be subjected to other types of loading. The length of the unwelded spaces between continuous sections of weld should not, however, exceed 12 in.

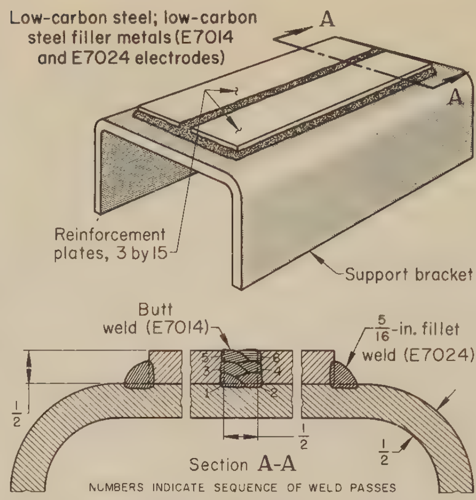


Fig. 27. Support bracket to which reinforcement plates were joined by horizontal fillet welds and then a six-pass square-groove weld (Example 4)

Groove Welds

For making a full-penetration square-groove weld, the electrode must be of a size that permits fusion of the weld root and gives proper arc length.

The amount of penetration obtained varies with the welding technique used. Even a very shallow weld puddle under the arc will form an insulating layer and thus decrease the penetrating power of the arc. When the electrode is raised to keep the tip out of the molten metal, the resulting longer arc dissipates more of its heat into the air, and in flaring out widens the weld bead. The welder should therefore maintain a short arc and the correct electrode angle. This will automatically force the weld puddle away from under the electrode tip, especially when travel speed is high. With heavily covered electrodes, the correct arc length will be obtained when the electrode is dragged along the joint with the covering touching the workpieces.

Smooth square-groove welds are readily produced on thicknesses of 0.060 to 3⁄16 in. (typical procedure for welding of thin sections is discussed on page 17), but for thicknesses of 3⁄16 to ¼ in. roughness is often a problem.

In the next example, a square-groove butt weld was used to fill a relatively wide opening, with little distortion.

Example 4. Use of a Six-Pass Square-Groove Butt Weld With Horizontal Fillet Welds (Fig. 27)

Figure 27 shows a low-carbon steel support bracket to which two ½-in.-thick reinforcement plates were joined — first, with 5⁄16-in. horizontal fillet welds, then with a six-pass square-groove weld in the ½-in. opening between the plates (section A-A).

The fillet welds were single-pass welds made with 7⁄32-in. E7024 electrodes at 325 amp, dcsp. For the square-groove weld, 5⁄32-in. E7014 electrodes were used, at 200 amp, dcsp. Cleaning with an air-operated chipping hammer followed each pass. Total time for each weldment was 12½ min.

The support bracket was designed with two support plates (instead of one larger plate) to minimize distortion in the weldment. The two-plate design eliminated the need for postweld straightening.

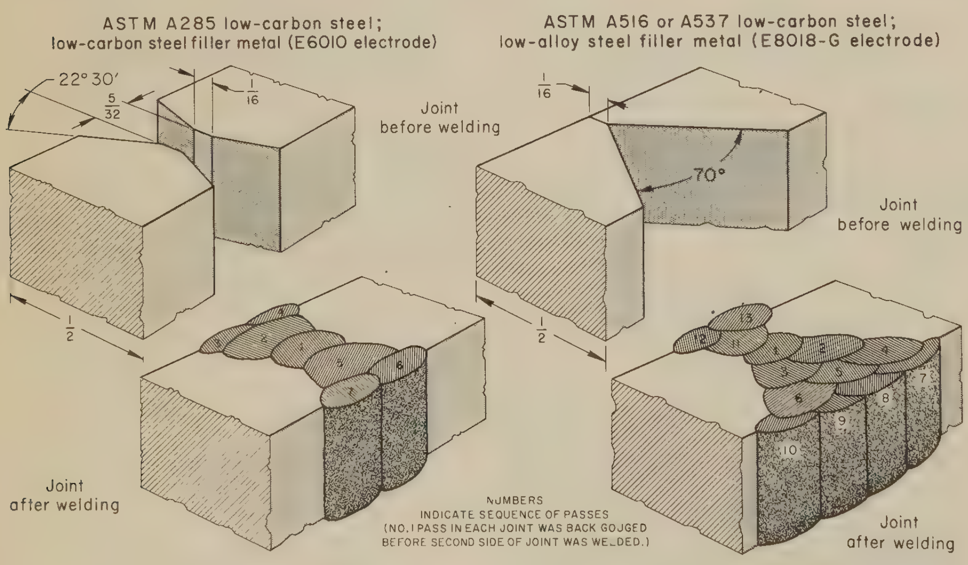
The service requirements of a weldment often influence joint design and welding procedure for groove welds. For example, the weld type (joint design), electrode class and size, number of passes, and the direction of welding for vertical seams in storage tanks usually depend on whether the tanks will be subjected to extremely low temperature or to normal temperature in service. Differences in the joint design and welding procedure for tanks intended for these two types of service are described in the next example.

Example 5. Use of Different Steels, Joint Grooves and Welding Procedures for Tanks Used at Normal and at Low Temperatures (Fig. 28)

Vertical joints in tanks intended for storage of anhydrous ammonia at −28 F were designed and welded differently from those in tanks designed for service at normal temperatures (ranging from outdoor ambient to that of hot asphalt). Figure 28 compares the two joint designs and shows the number and sequence of passes made in welding each. Welding conditions are compared in the table that accompanies Fig. 28.

Tanks for normal service were made of various grades of ASTM A285 low-carbon steel. A double-V-groove joint (Fig. 28a) was used to minimize the amount of deposited metal and to allow enough room for the electrode. E6010 electrodes were used because of their low cost. As shown in Fig. 28(a), the joint was welded in seven passes. Beads in passes 1, 2 and 5 were made with 5⁄32-in. electrodes in the vertical-up position. Beads in passes 3, 4, 6 and 7 (wash passes) were made with 3⁄16-in. electrodes in the vertical-down position. As shown in Fig. 28, pass 1 was back gouged (air carbon-arc) before welding the second side (pass 5). Back gouging was done with a 5⁄16-in.-diam carbon electrode at 300 to 350 amp.

Tanks for low-temperature service were of various grades of ASTM A516 or A537 low-carbon steel. A single-V-groove joint (Fig. 28b) was selected to provide good access and room for electrode manipulation



(a) Joint in tank for normal service (double-V-groove) (b) Joint in tank for low-temperature service (single-V-groove)

Edge preparation ....Gas cut and descale	Voltage and current (dcrp)(b):
Preheat ....None, for workpieces above 32 F(a)	5⁄32-in. E6010 ....26 to 29 v, 120 to 130 amp
Electrode class and size:	3⁄16-in. E6010 ....26 to 29 v, 150 to 170 amp
Double-V-groove weld ...E6010, 5⁄32 and 3⁄16 in.	⅛-in. E8018-G .....20 to 22 v, 125 to 135 amp
Single-V-groove weld ....E8018-G, ⅛ in.	Deposition rate, lb per hour:
Welding positions:	5⁄32-in. E6010 ....2.54
5⁄32-in. E6010 ....Vertical-up	3⁄16-in. E6010 ....3.66
3⁄16-in. E6010 and ⅛-in. E8018-G .Vertical-down	⅛-in. E8018-G 2.52

(a) Workpieces below 32 F were heated with a gas burner until they were warm to the hand. (b) Supplied by a motor-generator or a transformer-rectifier.

Fig. 28. Groove designs and buildup sequences for vertical butt welds in storage tanks for normal service and low-temperature (−28 F) service (Example 5)

for the ½-in. plate thickness. As Fig. 28(b) shows, the joint was welded in 13 passes (ten on one side and three on the other); pass 1 was back gouged before pass 11 was made. Beads in all passes were made with ⅛-in. E8018-G low-alloy steel electrodes (iron-powder, low-hydrogen covering) in the vertical-down position, to minimize heat input and to obtain the greatest tempering effect on previous beads.

For many large storage tanks, the plates are not all of the same thickness. For instance, the lowest ring of a tank that was 120 ft in diameter and 48 ft high had a plate thickness of 0.83 in. The plate thickness of the other rings decreased as tank height increased; the thickness of the second ring was 11⁄16 in.; the third, 9⁄16 in.; the fourth, 0.41 in.; and the fifth and sixth, 5⁄16 in. An alternative approach in fabricating storage tanks is to use steels of various strengths and the same wall thickness, which sometimes reduces welding cost.

Wash passes, such as passes 3, 4, 6 and 7 in Fig. 28(a), are often used in welding seams in tanks. These light finishing passes blend and smooth the bead, improving corrosion resistance.

Thin Sections

The minimum thickness of low-carbon steel that can be welded by the shielded metal-arc process depends on welder skill, welding position, characteristics of the current, type of joint, fit-up, class and size of electrode, amperage, arc length, and welding speed.

Low-carbon steel sheet as thin as 0.036 in. has been welded successfully with flux-covered electrodes. Welding sheet this thin, however, requires exceptional skill and the use of electrodes smaller than 3⁄32 in. Fit-up and position must also be most favorable. Generally, the minimum practical sheet thickness for an average welder is 0.060 in. Procedures for welding steel sheet 0.060 in. thick are given in the paragraphs that follow; a typical procedure is given in Table 14. (See also Recommended Proportions of Grooves, pages 148 to 150.)

Electrodes used should be 3⁄32-in. or 1⁄16-in. E6012 or E6013, preferably with direct current, straight polarity. These electrodes can be used in all positions. If welds are vertical, however, the weld metal is deposited from top to bottom (vertical-down). Of the two types of electrodes, E6012 produces a smaller bead, with moderate penetration. E6013 electrodes, although depositing a larger bead, provide a very soft, low-penetrating arc, and therefore are often preferred for welding thin sheet. When only alternating current is available, E6013 electrodes are preferred for easier starting and arc maintenance.

Fit-up. Tight-fitting joints are essential for producing good welds at maximum welding speeds. At normal levels of welding current, even slight root openings, particularly in butt joints, may cause excessive melt-through, necessitating considerable repair work. Current can be reduced to prevent melt-through when fit-up is poor, but this makes the arc difficult to maintain and reduces welding speed. Melt-through due to poor fit-up can be minimized by the use of copper backing strips, if this is practical. Typical effects of poor fit-up are illustrated in Fig. 25.

Table 14. Typical Procedure for Shielded Metal-Arc Welding Square-Groove Butt Welds in 0.060-In.-Thick Steel Sheet

Electrode. Use 3⁄32-in. E6012 or E6013.
Current. Straight-polarity direct current, 50 to 60 amp at start; vary amperage as required. E6013 electrodes require slightly higher current than E6012 electrodes.
Welding Position. Keep longitudinal axis of joint within 45° to 60° from horizontal. Increasing the slope of the joint decreases both the penetration and the size of the weld; decreasing the slope does the opposite.
Technique. Weld from top to bottom, using a light drag technique with sufficient speed of travel to lead the weld puddle and slag. Electrode lead angle should be 10° to 30°.

Welding Speed and Current. With tight-fitting joints, welding should be done with the highest current and travel speed practical. The proper welding speed is obtained for any set of variables when electrode travel is fast enough to permit the arc to lead the weld puddle, but slow enough to provide the desired bead shape without undercut.

Welding speeds for 0.060-in.-thick steel sheet are so high compared with speeds for thicker sections that welders inexperienced in welding thin sections have difficulty in keeping the arc on the joint. To concentrate the arc on the joint, thus minimizing heat input, welding should be done with a slight drag technique — that is, the tip of the flux covering should lightly touch the work as the electrode is advanced.

Positioning the work so that the axis of the joint to be welded is 45° to 60° from horizontal enables maximum efficiency with good control over the weld deposit, permits the use of maximum welding current and travel speed, and minimizes melt-through.

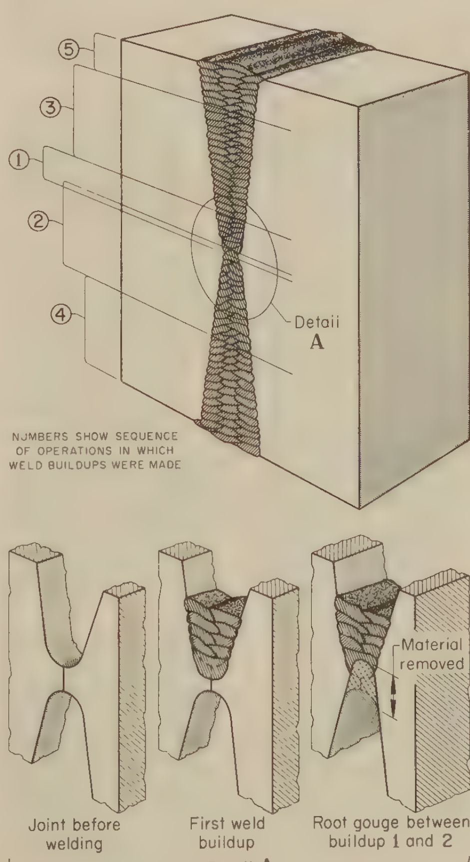


Fig. 29. Typical sequence of buildups in welding of thick sections with a double-U groove, using a root gouge between the first and second buildups

Tack welds should be as small as possible, because weld beads pile up when deposited over them. When uniform welds are required, it is beneficial to grind tack welds before welding, or to deposit them on the opposite side of the joint from which welding is to be done. Tack welds should be close enough to one another to prevent sheets from separating ahead of the arc. Separation of sheets is most prevalent in lap joints.

Thick Sections

All commercial thicknesses of low-carbon steel plate can be welded successfully by the shielded metal-arc process, provided that the root of the joint can be reached with the electrode.

Beveling is used on thicknesses above 3⁄16 or ¼ in. (see Recommended Proportions of Grooves, pages 148 to 150). A single groove is used on thicknesses up to about ¾ in.; a double groove is needed on thicker sections.

Three joint designs used in groove welding of sections over 4 in. thick are illustrated in Fig. 23. Figure 29 shows a typical sequence for welding thick sections with a double-U groove, using the root-gouging technique. In root gouging, the first buildup is made with a series of passes, as shown in the middle view in detail A in Fig. 29. The root of the weld is then gouged (usually by gas cutting or air carbon-arc cutting), as shown in the view at right in detail A in Fig. 29. The sequence of additional buildup operations, each of which consists of a series of passes, is shown in the top view in Fig. 29.

The major troubles that can occur in welding of thick sections are slag entrapment, porosity, transverse shrinkage (discussed below), angular distortion (discussed under "Distortion in Thick Sections", page 18), and cracking (see section "Causes and Prevention of Weld Defects", pages 18 to 20).

Transverse shrinkage is affected by restraint, volume of deposited weld metal, and welding procedure. Transverse shrinkage, which can be ¼ in. or more in full-section welds in plate 6 in. and upward in thickness, cannot be prevented, but it can be controlled or minimized by the use of one or more of the following design or welding practices:

1 Design groove joints for minimum volume of weld metal.
2 Weld temporary strongbacks across the joints before welding.
3 Use a block sequence in welding.
4 Make allowances in design to compensate for estimated shrinkage.
5 Peen all but the root and cover passes, using a blunt-nose tool. Peening should flatten the surface of the weld bead, but not cut into it. To retain notch toughness, do not peen at 500 to 900 F.

Sections of Unequal Thickness

In shielded metal-arc welding, as in other welding processes, special techniques are required when the components to be welded have a large

heat-sink differential (difference in heat-dissipating capacities).

When a thick member is joined to a thin member, the welding current needed to obtain good penetration into the thick member is sometimes too much for the thin member and will result in undercutting of the edges of the thin member and in a poor weld. If the proper amount of current for the thin member is used, the heat will not be sufficient to provide adequate fusion in the thick member, and again a poor weld will result.

A typical application involving components of unequal section thicknesses is the welding of heat-exchanger tubes having 0.093-in. wall thickness to a tube sheet as thick as 10 in. Here, the usual method of avoiding difficulty is to cut a ¼-in.-deep circular groove in the upper surface of the tube sheet around the opening for the tube, as shown in Fig. 30. By restricting heat transfer, this groove minimizes the heat-sink differential between the thin tube wall and thick tube sheet.

A more widely applicable method of minimizing heat-sink differential is to place a copper backing block against the thin member during welding (Fig. 31). The block serves as a chill, or "heat robber", for the thin member. It can be beveled along one edge so that it can be used when horizontal fillet welds are deposited on both sides of a thin member, as in Fig. 31. Copper backing bars or strips are made in a variety of shapes and sizes, to dissipate heat as needed. Often some experimentation is required to obtain the optimum backing location and design.

Another way to obtain equalized heating and at the same time obtain smooth transfer of stress where unequal section thicknesses are being welded is to taper one or both members to obtain a common width or thickness at the joint.

Distortion

Welding of any structure or member results in nonuniform heating and cooling at the point of welding. Thus it follows that welding will be accompanied by some distortion, and some unbalanced residual stress will be present. In practice, the amount of distortion from welding depends on several factors. In some weldments distortion may be so slight that it may be disregarded, while in others it may be so great that special precautions must be taken before welding, or straightening must be done after welding.

In many welded structures the residual stresses have little influence on the service life of the structure. On the other hand, in structures that are subjected to dynamic loading or those that must retain their shape and not distort during their service life, residual stresses are important.

Use of the following practices may assist in control of detrimental stresses and distortion which could impair the usability of a weldment:

1 The forming and preparation of steel sheet and plate induce stresses within the material. These may be released by the heat of welding and cause substantial difficulties. Thus, stress relieving of the components before welding is sometimes required.
2 On multiple-pass welds, angular distortion across the welded joint will increase with the number of passes.
3 A more uniform distribution of heat in a longitudinal seam can be obtained by welding with a backstep sequence or a wandering (skip) sequence. This practice also gives greater rigidity to the seam and results in less distortion.
4 Clamping will not entirely eliminate warping, but is more likely to be effective if the weld is permitted to remain in the clamps until cooled.
5 Peening the weld metal while it is hot has been very effectively used to reduce stresses and to minimize distortion or warping. (However, it is generally desirable to avoid peening in the temperature range of 500 to 900 F, because peening in this range may result in loss of notch toughness.)
6 Stresses may be substantially reduced if welding direction is away from the point of greatest restraint.
7 Changing the speed of welding may either increase or decrease distortion of the weldment. Experimentation may be essential to determine the optimum welding speed for specific joints where freedom from distortion is critical.
8 Residual stresses may be minimized by postweld heat treatment of the completed weldment. Proper support of the weldment is required to prevent warpage and distortion from occurring during stress relief.
9 Welding of parallel joints in opposite directions can sometimes minimize distortion (see Example 3 and Fig. 14).
10 Balancing of stresses by the use of a double groove, or by alternating the welding from one side of the joint to the other (as shown in Fig. 29).

Distortion in Thin Sections. Distortion or buckling is more often encountered in the welding of thin sheet. To minimize distortion, beads should be small and should be deposited as rapidly as possible. The cross section of any weld deposited on 0.060-in.-thick steel will normally be larger than that required for full strength (based on metal thickness). Intermittent welds, clamping fixtures, and copper backing bars effectively minimize distortion.

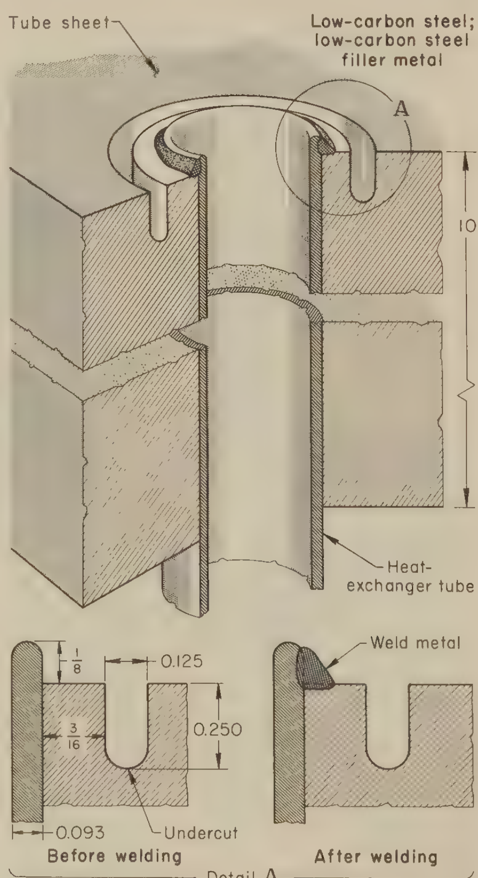


Fig. 30. Thick tube sheet with machined groove for minimizing heat-sink differential during welding of the thin-wall heat-exchanger tube to the tube sheet

Distortion in Thick Sections. Welding of thick sections is accompanied by angular distortion, which is caused by unequal shrinkage across the welded joint. Unequal shrinkage occurs because the welds are deposited in successive layers and because, in most joint designs, the width of the layers increases as the joint is filled.

Eliminating angular distortion in the welding of thick sections is virtually impossible when all welding is from one side. Temporary strongbacks, built-in ribbing, block-sequence welding, preheating, and peening will help to reduce angular distortion.

When individual plates a few inches thick are to be butt welded, presetting the plates opposite to the anticipated direction of angular distortion is effective for offsetting most of the distortion; during welding, the plates are permitted to move as a result of weld shrinkage into a flat plane. However, presetting is seldom possible when the thick sections to be welded are integral parts of structures. Also, presetting is impractical when sections 6 in. thick and thicker are welded from one side, because angular movement resulting from contraction of weld metal will tear apart the joint at the weld root.

Whenever possible, heavy sections should be welded from both sides. Joints should be designed so that both sides require the same volume of weld metal, and a balanced welding technique should be used (see Fig. 29). Balancing the welding on both sides of the joint results in good control over angular distortion, but when welding is done in the flat position, the workpiece must be turned over frequently, unless restraining devices are used.

Joint design is important for control of distortion. Groove angles should be the minimum size that will allow root penetration and accessibility for remaining passes.

Sequencing. Establishing the order of deposit in which the several passes in a weldment will be made is called sequencing. It may be extremely important to the final usability of the weldment that the welds be deposited in a precise order (buildup sequence). For pilot models of critical weldments, it may be necessary to change the sequence several times to obtain the optimum order of passes.

Causes and Prevention of Weld Defects

In the shielded metal-arc welding of steel, slag inclusions and porosity are common weld defects. Other defects that often occur are undercuts, longitudinal (centerline) cracks, underbead cracks, and gaps resulting from incomplete fusion. The appearance and usual locations of these defects are shown in

Fig. 32. Probable causes of several types of weld defects in steel, together with methods of prevention, are discussed in the paragraphs that follow.

Slag inclusions (Fig. 32a) may be the result of (*a*) incomplete deslagging of a previous pass; (*b*) wide weaving, which permits slag to solidify at the sides of the bead; (*c*) erratic progression of travel; (*d*) excessive amounts of slag ahead of the arc, particularly in deep grooves; and (*e*) use of electrodes that are too large. The preventive measures are, respectively: (*a*) to deslag deposits thoroughly before a subsequent weld bead is deposited; (*b*) to restrict the width of weaving so that the entire width of the slag immediately behind the weld puddle remains molten; (*c*) to use a uniform travel speed; (*d*) to keep slag behind the arc by shortening the arc, increasing the electrode angle, or increasing travel speed; (*e*) to use a smaller electrode.

Wagon Tracks. Linear slag inclusions along the axis of the weld are sometimes called "wagon tracks". They ordinarily result from failure to remove slag remaining from previous passes, or from allowing slag to run ahead of the weld puddle. Wagon tracks above the root pass have the same effect on weld quality as other inclusions in the weld metal or base metal.

Porosity that is scattered along the entire length of a weld bead (Fig. 32b) can be caused by (*a*) impurities, such as sulfur or phosphorus, in the work metal; (*b*) contamination of the surface of the work metal by rust, grease, moisture or dirt; (*c*) excessive moisture in electrode coverings; (*d*) improper arc length; (*e*) excessive current; (*f*) welding at a speed too high to permit gases to escape; and (*g*) freezing of the weld puddle before gases escape. The steps for avoiding the above causes of this type of porosity are, respectively: (*a*) changing to work metal of a different composition; (*b*) cleaning the work metal, and removing moisture from joint surfaces; (*c*) redrying electrodes to restore recommended moisture content of coverings (see Table 7); (*d*) using proper length of arc; (*e*) reducing welding current; (*f*) reducing travel speed to permit gases to escape; and (*g*) preheating the work metal or using a different class of electrode, or both.

When porosity occurs within the first ¼ to ½ in. of bead length, the most likely cause is moisture in the covering of the electrode — particularly if the electrode is of the low-hydrogen type. The remedy is to use dry electrodes.

Sometimes porosity occurs within the last inch or two of the weld bead when E6010, E6011 or E6012 electrodes are used. The usual cause is excessive current, which results in overheating and excessive drying of the flux covering. When this occurs, the current should be reduced to the recommended range.

"Wormhole" porosity (see Fig. 32c) is usually associated with moisture entrapped in the joint; when visible at the surface, wormhole porosity is sometimes referred to as "gas shoots". Sulfur in the base metal is also a contributing factor. One means of preventing wormhole porosity is to reduce travel speed to permit gases to escape before the metal freezes.

Undercuts (Fig. 32d) are usually due to excessive welding current, arc length and weaving speed. In horizontal or vertical welding, additional causes are excessive electrode size and incorrect electrode angles. Travel speed should be such that the deposited weld metal completely fills all melted-out portions of the base metal, and when the weaving technique is used, there should be a slight pause at each side of the weld. The arc should be as short as possible without shorting, and current should be appropriate for the electrode size and type and for the welding position.

Hot cracking occurs at elevated temperature, generally just after the weld starts to solidify. Hot cracks, which are for the most part intergranular, can be identified by a coating of oxide on their surfaces. Depending on the magnitude of strain, hot cracks will vary from microfissures to readily visible cracks.

Hot cracks are most likely to occur in the root-pass weld bead, because of the small cross section of the bead compared with the mass of material being welded. Hot cracking often occurs in deep-penetrating welds, and in welds in free-machining steels. If the initial crack is not repaired, it will usually continue through successive layers as they are deposited.

Hot cracking of the root bead may be minimized or prevented by preheating to modify strain, by increasing the cross-sectional area of the root bead, by using low-hydrogen electrodes, or by changing the contour or the composition of the weld bead.

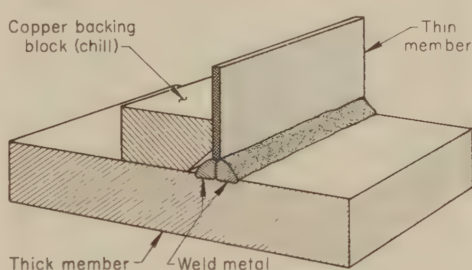


Fig. 31. Use of a copper backing block as a chill to minimize heat-sink differential in welding a thin member to a thick member

Cold cracking normally occurs in the heat-affected zone and near ambient temperature. Its occurrence may be delayed for as long as several days as stresses within the weldment relieve themselves. Cold cracking is generally recognized as being caused by excessive restraint of the joint, or by martensite formation as a result of rapid cooling. Low-hydrogen electrodes are used extensively to overcome cold cracking; preheating is also helpful. Although a stress-relief heat treatment cannot heal cracks that have already formed, it does reduce the residual stress sensitivity from welding, thus reducing susceptibility to fracture.

Centerline cracks (Fig. 32e) are cold cracks that often occur in single-pass concave fillet welds. The usual causes are an incorrect relationship between the size of the weld and the thickness of the work metal, poor fit-up, and overly rigid fit-up.

The usual ways of preventing centerline cracks are (*a*) positioning the joint slightly uphill so as to produce flat or slightly convex bead contours; (*b*) increasing bead size; (*c*) decreasing gap width or filling one side of the joint before welding the parts together; and (*d*) providing a small gap to allow movement during cooling.

Centerline cracks can occur as extensions of cracks in weld craters (see page 20) or root-bead cracks. The first extension of the crack may occur after the weld is completed and is cooling.

In one application of multiple-pass welding, centerline cracking occurred when an E6011 electrode was used for the root pass, an E6012 for the intermediate passes, and an E6020 for the final pass. The cracking was eliminated by reducing the number of passes with the E6012 electrode and increasing the depth of deposit with the E6020 electrode in the final pass.

Underbead cracks (Fig. 32f) are most frequently encountered when welding a hardenable base metal. Excessive joint restraint and the presence of hydrogen are contributing causes. Underbead cracking can be minimized or prevented by using low-hydrogen electrodes or by preheating joints to the temperature range of 250 to 400 F.

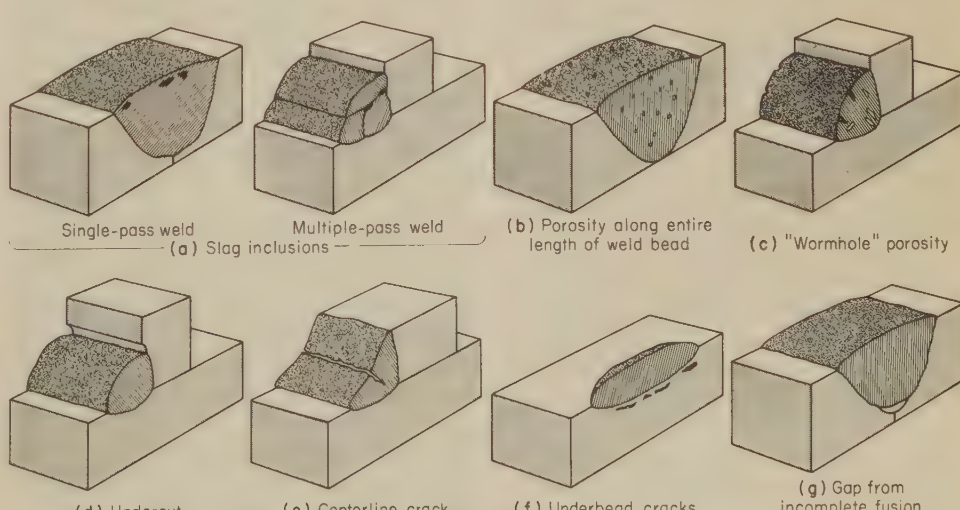


Fig. 32. Appearance and location of several common types of defects that can occur in welds made by the shielded metal-arc process

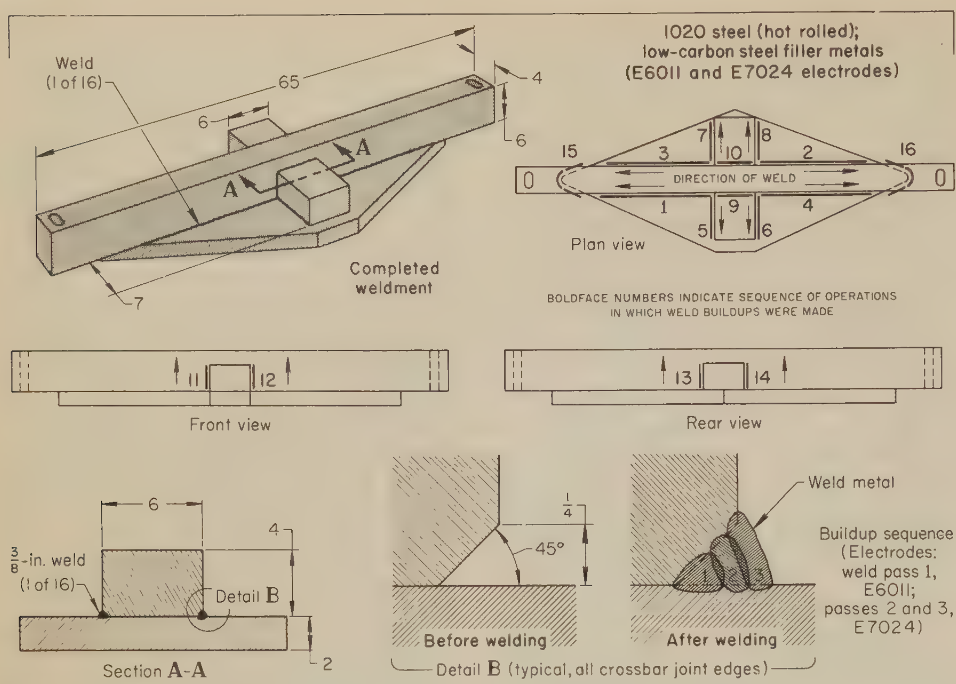


Fig. 33. Truck-axle weldment joined with 16 welds, in which cracking was prevented by beveling joint edges of the two 7-in.-long crossbars, welding in three passes instead of two, and welding in directions of decreasing restraint, in the sequence shown (Example 6)

Base-metal cracking usually originates in the heat-affected zone of the base metal as either hot or cold cracks. Cracks often extend into and through the weld metal. A reduction in welding stresses by, for instance, using weld metal with high ductility may alleviate the problem. The presence of a small slag inclusion or mass of porosity can increase the probability of cracking.

Cold cracks may originate at the toe of a weld and wander off in a random direction. Generally, increasing restraint of the base metal, increasing the thickness of the base metal, or increasing the length of the weld increases cold cracking. The probability can be decreased by preheating the base metal, by postheating after welding, by depositing the weld in an intermittent pattern, or by welding with higher currents.

Microfissuring can normally be detected only by the use of a microscope. It is caused by either hot or cold cracking. Extremely small cracks are not detrimental for many applications, but for applications involving fatigue, they make the weldment unacceptable.

Weld Craters. Weld craters are a recession of the surface and are caused by solidification of the molten weld puddle after the arc has been extinguished. Weld-crater cracks often serve as the origin of linear cracking. They are usually removed by chipping or grinding, and the depression is filled with a small deposit of filler metal.

A backstep or reverse-travel technique to fill each crater before breaking the arc has been found helpful in preventing crater cracking.

Arc Strikes. Striking the arc on the base metal outside the weld joint can result in hardened spots on the surface. Failures can occur due to notch effect. Welders should be cautioned to avoid indiscriminate marking of the base-metal surface with arc strikes, as it is unnecessary and may be harmful. Many codes prohibit striking the arc on workpiece surfaces.

Gaps from incomplete fusion may occur between the weld metal and the base metal (see Fig. 32g) or between the weld beads of a multiple-pass weld. Failure to obtain complete fusion can be caused by excessive travel speed, bridging, excessive electrode size, insufficient current, or poor joint preparation. Gaps usually can be prevented by reducing travel speed, improving joint preparation, or increasing the current.

Oxidation. Surface oxidation occurs when base metal or weld metal has been inadequately protected from the atmosphere. Severe drafts, which disrupt the protection offered by the gas shield, must be avoided, so that the weld metal and adjacent base metal are shielded until they have cooled enough to prevent harmful oxidation.

Sink or concavity is produced by surface tension on the surface of the weld puddle, which pulls the molten metal up into the joint, or by the effect of gravity when welding in the overhead position. If the condition is severe, root-bead cracking can result.

Weld Reinforcement. The reinforcement left on the weld can have a significant effect on the fatigue strength of the weldment at that point. It is customary on highly stressed weldments to remove the reinforcement by grinding it flush with the level of the adjacent base metal. Use of appropriate welding techniques will result in a weld reinforcement that is smoothly blended into the adjacent surface.

Overlapping (protrusion of the weld metal beyond the toe or root of the weld) is caused most often by (*a*) insufficient travel speed, which permits the weld puddle to get ahead of the electrode and cushion the arc; (*b*) incorrect electrode angle, which allows the force of the arc to push molten metal over unfused portions of the base metal; or (*c*) welding away from ground with large electrodes having very fluid weld puddles, such as E6020, E6027, E7024 and E7028.

To prevent overlapping, the travel speed should be such that the arc leads the weld puddle, and the electrode angle should be such that the force of the arc does not push the molten metal out of the puddle and over the cold base metal. Overlapping is corrected by grinding off the excess weld metal.

Excessive weld spatter, if coarse, often is caused by an excessive arc length; if the spatter is fine, excessive current is a likely cause. Weld spatter can be minimized by keeping the arc length at the minimum that will not result in shorting out. A slight drag technique is recommended when using electrodes with iron-powder coverings. Current should be kept within the range recommended for the specific electrode. To improve the surface appearance of the weld, spatter can be removed by grinding.

Effect of Number of Passes. The use of multiple passes is often effective in the prevention of weld cracks. For instance, multiple passes can be effective in fillet welding when cracking has resulted from single-pass welding, either because the carbon equivalent of the steel was borderline or because attempts to minimize distortion caused severe joint restraint in cooling.

The use of multiple passes (preferably a minimum of three) can sometimes eliminate the need for preheating or postheating when conditions are borderline. In multiple-pass welding, the first pass provides some preheating effect for the second pass, and the third pass provides a certain amount of postheating effect for the previous two passes, and so on. Welding should be done quickly, to minimize cooling between passes. Also, the first-pass weld bead must be deep-penetrating, and must be of sufficient size so that it will be strong enough to resist cracking. (If the first-pass bead cracks, the crack will usually propagate through subsequent beads.)

This technique is particularly adaptable to repair welding in the field, and has proved helpful in shop-welding applications as well (see Example 6). It should not be assumed, however, that the technique can always be considered as a substitute for preheating and postheating.

Cracking From Multiple Causes. In shop practice, weld cracking often has two or more causes, rather than a single cause. An application in which this occurred, and the series of corrective steps that were necessary before acceptable welds were produced, are described in the example that follows.

Example 6. Changes in Welding Procedure To Prevent Cracking (Fig. 33)

Figure 33 shows a four-piece 840-lb 1020 steel truck-axle weldment that required 16 fillet welds. In the original procedure, all of the ⅜-in. fillet welds were deposited in two passes with E7024 electrodes. Although the high degree of restraint during cooling of a 2-in.-thick plate would normally indicate the need for preheating to at least 200 F and possibly postheating for stress relief, welding trials made without heating appeared to be satisfactory; no cracking

was detected. However, when the truck axles were put in service, cracks appeared in some of the welds. Because heating facilities were not available at the plant, welding procedures were changed, in an effort to prevent cracking.

In the first revision, the size of the fillet welds was increased to ½ in. This reduced the cracking but did not eliminate it.

In the second revision, fillet size was increased to ¾ in. This further reduced cracking, but magnetic-particle inspection showed occasional cracks in the corners and in the top fillet welds of the two 7-in.-long crossbars. In addition, cost and appearance of the ¾-in. fillet welds were objectionable.

The third revision involved welding in the directions of decreasing restraint, in the sequence shown in Fig. 33. This also reduced cracking, but did not eliminate it.

In a fourth revision, the class of electrodes was changed — first, to low-hydrogen types (with tensile strengths of 70,000 to 110,000 psi), and then, because of their greater ductility, to austenitic stainless steel electrodes — but neither change resulted in a satisfactory solution to the problem.

Finally, the welds were made in three passes (rather than two, as in all previous procedures); a deep-penetrating root pass with a 5⁄32-in. E6011 electrode was followed immediately by two passes with 3⁄16-in. E7024 electrodes. This procedure greatly reduced the amount of cracking — largely because of the preheating effect of the first and second passes. A further improvement was obtained by cutting a ¼-in. bevel on the joint edges of the 7-in.-long crossbars (see detail B in Fig. 33), to increase penetration. Weld size was changed back to ⅜ in.

The three-pass welding and the edge beveling, in combination with the use of the directional welding sequence shown in Fig. 33, eliminated weld cracking.

Rating of Weldability

Some factors that determine whether a steel of a specific composition can be welded by conventional procedures include flexibility or rigidity of the structure, cooling conditions, skill of the welder, and weld-quality requirements. Welds that are good enough for many commercial applications can be made in low-carbon steel that has an abnormal content of inclusions, but these welds would not be good enough for severe service conditions. Furthermore, a steel that contains an abnormal content of carbon or alloying elements may be unsuitable for welding into complex structures, but completely satisfactory for simple structures. Resulfurized steels are highly susceptible to underbead cracking, porosity and hot cracking. In many applications, however, resulfurized steels can be successfully welded with low-hydrogen electrodes.

The weldability of a steel in terms of its susceptibility to cracking can be roughly estimated by use of a carbon equivalent (*CE*), which can be calculated using one of several formulas, such as the following equation (for other equations, see the article on Arc Welding of Alloy Steels, page 200):

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr}{5} + \frac{\%Mo}{4}$$

With this equation, it has been suggested that if the carbon equivalent is not more than 0.45%, the steel is considered weldable without any special precautions, such as preheating, postheating, or the use of low-hydrogen electrodes or of additional passes. However, weldability is dependent upon section thickness, as discussed on page 188 in the article on Arc Welding of Hardenable Carbon Steels.

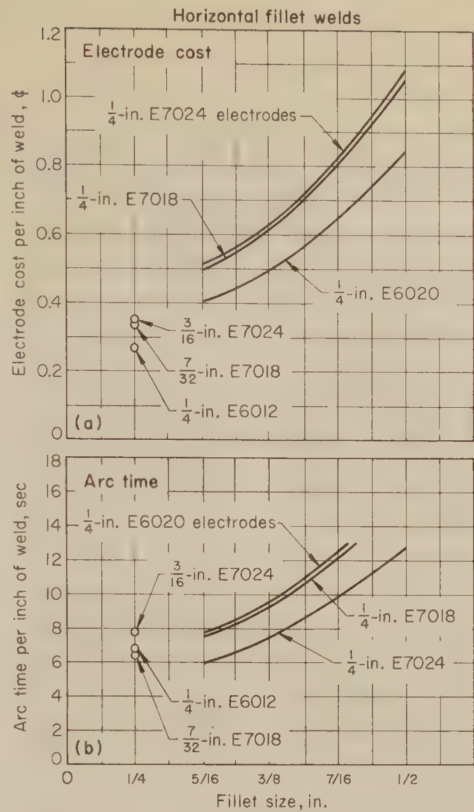


Fig. 34. Effect of electrode selection on electrode cost and on arc time for horizontal fillet welds of various sizes

Most high-strength low-alloy structural steels do not present serious problems in welding, even if their alloy content is high enough to raise their carbon equivalent above 0.45%. Welding practice for such steels, and for higher-alloy steels, is dealt with in the article on Arc Welding of Alloy Steels, which begins on page 200.

Effect of Surface Condition on Weld Quality

Many satisfactory welds are made without surface preparation, but quality is not usually high in such welds. The most common surface contaminants that adversely affect weld quality are carburization (resulting usually from improperly done gas or arc cutting), oxides and mill scale, shop dirt (usually oil and grease), paint, and moisture.

Surface carburization can result in cracking, because, in effect, a high-carbon steel is being welded. Carburized surfaces can be removed by grinding or other mechanical means.

The other contaminants listed above can result in weld porosity, or sometimes microporosity (which usually cannot be detected without magnification).

Abrasive blasting is a widely used method for removing mill scale, rust or other oxides in production welding. Grinding is used for odd jobs or for weldments that cannot be conveniently blasted. Oil and grease can be readily removed by wiping with a clean solvent, and then washing and drying if necessary. Paint must be removed from surfaces to be welded.

Moisture frequently is present on components that are welded outdoors or on components that are brought indoors just before welding. A humid atmosphere often causes a layer of moisture to form on workpiece surfaces. Surfaces should always be dry before welding. A gas torch may be used to drive off surface moisture.

In the following example, removal of surface oxide markedly improved weld quality.

Example 7. Use of Shot Blasting To Remove Surface Oxide and Reduce Porosity

Components of fuel tanks for industrial trucks were joined by shielded metal-arc welding. The components were made of hot rolled low-carbon steel ⅜ in. thick.

Originally, the completed weldment was shot blasted, but the components were not cleaned before welding. Although the surfaces to be welded were normally free from grease and oil, some tightly adherent oxide or mill scale was present on them; as a result, approximately 25% of the tanks leaked, because of porosity in the welds, and required repair.

When the procedure was changed so that shot blasting preceded welding, only 5% of the tanks leaked and the number of leaks per tank was reduced, as shown by the following comparison for an average lot size of 20 tanks:

Item	Shot blasting — After welding	Shot blasting — Before welding
Leaky tanks per lot	5	1
Leaks per tank	3	1
Time for repair and testing, minutes:		
Each tank	17	12
Total per lot	85	12

Cost

Many cost studies made to compare shielded metal-arc with submerged-arc welding and gas metal-arc welding have shown that, when welding conditions (mainly welding position, accessibility, and the amount of welding done without changing classes or sizes of electrodes) are favorable, shielded metal-arc welding is the most costly of the three processes. (See the examples that deal with costs in the articles on Submerged-Arc Welding and Gas Metal-Arc Welding in this volume.) Cost studies have also shown that if shielded metal-arc welding is used in a production application and electrodes of the same class and size are used for more than half the welding time, the use of a process that utilizes a continuously fed electrode should be considered.

Conversely, in applications where welding must be done in a variety of positions, or some areas are difficult to reach, or where specifications require frequent changes in class and size of electrode (or where all three conditions prevail), shielded metal-arc welding often is the lowest-cost process, and may well be the only practical one.

Effect of Electrode Selection on Welding Cost. Cost of electrodes and electrode performance must both be evaluated in calculating the effect of electrode selection on welding cost. Figure 34 compares electrode cost and arc time per inch of weld for horizontal fillet welds of various sizes made with electrodes of four different classes. Note that for ¼-in. electrodes used in making fillet welds ranging in size from 5⁄16 to ½ in., E7024 electrodes cost the most

but had the shortest arc times (best performance); at the opposite extreme, E6020 electrodes cost the least but had the longest arc times.

The example that follows presents a detailed analysis of costs for the use of E6013 versus E7024 electrodes in making ¼-in. horizontal fillet welds.

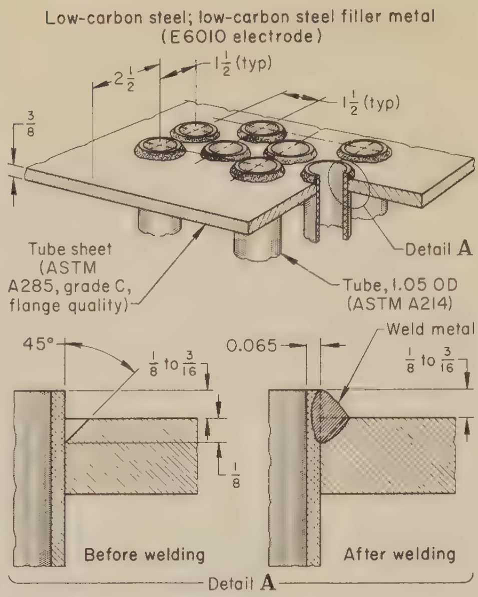
Example 8. Change From E6013 to E7024 Electrodes To Reduce Welding Cost (Table 15)

A cost study was made to compare the costs of ¼-in. horizontal fillet welds made with a conventional, all-position electrode (E6013) and with an iron-powder electrode (E7024). Three electrodes of each type were used for welding test pieces that consisted of two plates tack welded to form a T-section. Results of the cost study are presented in detail in Table 15. As this comparison shows, total cost was reduced nearly 10% when the E7024 electrodes were used, mainly because of decreased arc time. The E7024 electrodes cost slightly more per pound than the E6013, but this increase in electrode cost was partly offset by the decrease in weight of electrode used per inch of weld with the E7024 electrodes.

A disadvantage of the cost comparison in Example 8 is that all electrode variables cannot be evaluated without experience on similar jobs or additional data on the actual job. Cleaning costs, for instance, were not included.

Costs for chipping and repairing of defective welds are often major, and should be included in welding costs for assemblies.

Another variable is the ease of operation or the skill required to use an electrode. For example, a skilled welder might produce a horizontal fillet weld of good quality with a high-speed electrode, but an inexperienced welder might require a slower electrode to produce a fillet weld of equal quality.



Joint type	Circumferential corner
Weld type	Partial-penetration groove
Edge preparation	Holes drilled and beveled
Preheat	None (metal at 70 F min)
Welding position	Flat
Number of passes	One
Electrode	⅛-in. E6010, 12 to 14 in. long
Power supply	400-amp motor-generator
Current	80 to 120 amp, dcrp
Voltage	24 to 28 v
Arc length	⅛ to 3/16 in.
Electrode consumption	3 welds per electrode
Postheat	None

Shielded metal-arc welding was used because the available automatic machine for gas metal-arc welding (the process that had originally been used) could not accommodate the varying projection (⅛ to 3/16 in.) of the tubes above the tube sheet.

Fig. 35. Tube-to-tube-sheet weldment that was shielded metal-arc welded under the conditions shown in the table (Example 10)

When quality requirements are stringent, analysis must include the cost of inspection and repair. In the following example, cost analysis including costs for repair and reinspection showed that the use of more costly electrodes reduced welding cost.

Example 9. Cost Analysis Including Costs for Repair and Reinspection for E6010 or E6013 Electrodes vs Low-Hydrogen Electrodes

Repairs and reinspections were required in about 20% of the length of butt welds made in pressure vessels with E6010 or E6013 electrodes, but in only about 5% of the length of welds made with low-hydrogen electrodes. Although the low-hydrogen electrodes had a higher initial cost than the E6010 or E6013 electrodes, their use reduced the total cost of welding, as the following analysis shows:

- 1.0 = the cost of E6010 or E6013 electrodes plus the cost of depositing 1 ft of butt weld.
- 1.5 = the cost of low-hydrogen electrodes plus the cost of depositing 1 ft of butt weld.
- 5.0 = the cost of radiographing 1 ft of weld.
- 2.0 = the cost of repairing 1 ft of defective weld when E6010 or E6013 electrodes were used.
- 3.0 = the cost of repairing 1 ft of defective weld when low-hydrogen electrodes were used.

Using the five factors itemized above, the total relative costs for 100 ft of weld were calculated as follows:

E6010 or E6013 Electrodes (20% Repair)	
Original weld cost (100 × 1.0)	100.0
Inspection cost (100 × 5.0)	500.0
Repair cost (0.20 × 100 × 2.0)	40.0
Reinspection cost (0.20 × 100 × 5.0)	100.0
Total cost per 100 ft of weld	740.0
Cost per foot	7.4
Low-Hydrogen Electrodes (5% Repair)	
Original weld cost (100 × 1.5)	150.0
Inspection cost (100 × 5.0)	500.0
Repair cost (0.05 × 100 × 3.0)	15.0
Reinspection cost (0.05 × 100 × 5.0)	25.0
Total cost per 100 ft of weld	690.0
Cost per foot	6.9

Shielded Metal-Arc Welding vs Alternative Welding Processes

When more than one welding process can produce acceptable results, the choice depends primarily on equipment available, skill of the welders, number of similar weldments to be produced, and cost.

Shielded metal-arc welding is the most versatile arc welding process, but it is not always the lowest in cost or the fastest.

Although there are applications for which several welding processes may be suitable alternatives to shielded metal-arc welding, for most applications gas metal-arc welding and flux-cored arc welding are the two closely competitive processes. Both are faster than shielded metal-arc welding in terms of rate of metal deposited. Because both are semiautomatic processes (that is, the filler metal is supplied at an established rate from a coil), arc time can be a higher percentage of total time than in shielded metal-arc welding. In addition, both welding processes can be fully automated. Aside from these important advantages, however, gas metal-arc and flux-cored arc welding generally are less versatile than shielded metal-arc welding.

The two examples that follow describe applications for which shielded metal-arc welding was selected in preference to alternative processes.

Table 15. Analysis of Costs for Making ¼-In. Horizontal Fillet Welds With E7024 vs E6013 Electrodes, Computed From Rate of Welding (Example 8)

Data on Assembly To Be Welded	
Length of ¼-in. fillet weld specified on assembly drawing	250 in.
Labor cost per hour (including overhead)	$8.00
Labor time other than arc time required for making weld	16 min
Weight of linear inch of ¼-in. fillet weld	0.00884 lb

Item	3/16-in. E7024 electrode	1/4-in. E6013 electrode
Cost Comparison		
Electrode cost per pound	$0.14	$0.13
Weight of three electrodes	0.810 lb	0.931 lb
Weight of tacked specimen	10.00 lb	10.10 lb
Weight of specimen after welding	10.56 lb	10.72 lb
Weight of deposited metal	0.56 lb	0.62 lb
Arc time to make weld	3.85 min	5.32 min
Theoretical length of weld	$\frac{0.56}{0.00884} = 63.3$ in.	$\frac{0.62}{0.00884} = 70.1$ in.
Weight of electrode used per inch of weld	$\frac{0.810}{63.3} = 0.0128$ lb per in.	$\frac{0.931}{70.1} = 0.0133$ lb per in.
Cost of electrode to make an inch of weld	0.0128 × $0.14 = $0.00179	0.0133 × $0.13 = $0.00173
Time required to make an inch of weld	$\frac{3.85}{63.3} = 0.0608$ min per in.	$\frac{5.32}{70.1} = 0.0759$ min per in.
Labor cost per minute	$\frac{\$8.00}{60} = \$0.133$ per min	$\frac{\$8.00}{60} = \$0.133$ per min
Labor cost per inch of weld	$0.133 × 0.0608 = $0.00809 per in.	$0.133 × 0.0759 = $0.01010 per in.
Cost for arc time per inch of weld	Labor $0.00809 Electrode 0.00179 $0.00988 per in.	Labor $0.01010 Electrode 0.00173 $0.01183 per in.
Cost for arc time for assembly	250 × $0.00988 = $2.47	250 × $0.01183 = $2.96
Cost of labor other than for arc time	$0.133 × 16 = $2.13	$0.133 × 16 = $2.13
Total cost of welding assembly	$2.47 2.13 $4.60	$2.96 2.13 $5.09

Example 10. Change From Automatic Gas Metal-Arc Welding to Shielded Metal-Arc Welding Because of Wide Tolerances in Weldment Components (Fig. 35)

Figure 35 shows a tube-to-tube-sheet weldment used in a heat-transfer chamber for the condensation of refrigerant. Originally, automatic gas metal-arc welding was used for the partial-penetration groove welds in the circumferential corner joints (detail A in Fig. 35), but results were unacceptable because the head of the available automatic welding machine could not be adjusted for the varying projection (⅛ to $\frac{5}{16}$ in.) of the tubes above the tube sheet. For successful use of the machine, all tubes would have had to project a uniform distance. Because manufacturing tolerances were not that accurate, the process was changed to shielded metal-arc welding, under the conditions listed in the table that accompanies Fig. 35.

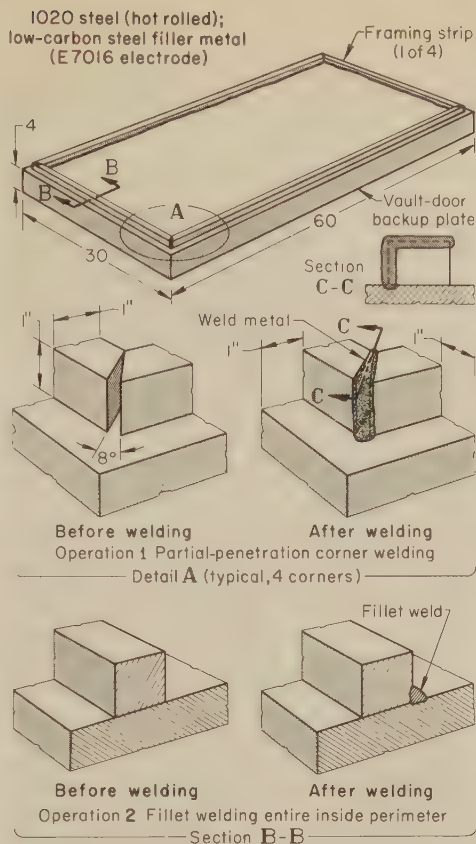
Shielded metal-arc welding, done in accordance with the ASME boiler code, produced complete fusion and leakproof joints (one leak in about 8000 welds). All joints were tested under water, with dry air at 300 psig.

Example 11. Use of Shielded Metal-Arc Welding Because of Low Production Quantity (Fig. 36)

For welding 1-in.-sq-bar framing strips to a vault-door backup plate (Fig. 36), shielded metal-arc welding was selected as the most practical process because production quantity was low. Both the plate and the framing strips were made of hot rolled 1020 steel.

After having been prefitted by gas cutting the edges at a 41° angle, the framing strips were positioned on top of the 30-by-60-in. backup plate and held in place with C-clamps.

Welding was done in two operations. First, the 1-in.-square bars were joined with partial-penetration welds at the corners (detail A and section C-C in Fig. 36) to form a frame (which served as a guide during final assembly of the vault door). Then the frame was joined to the plate by a fillet weld along the base of the entire inside perimeter of the frame (section B-B in Fig. 36). Quality was controlled by means of 100% visual inspection and spot checking with dye penetrant; rejection rate was zero.



Edge preparation (corner joints)	Gas cutting
Preheat and postheat	None
Welding positions	Vertical and horizontal
Number of passes per weld	One
Electrode	⅛-in. E7016, 14 in. long
Power supply	450-amp constant-voltage transformer-rectifier
Current	125 amp, dcrp
Voltage	22 to 24 v

Fig. 36. Vault-door backup plate to which framing strips were joined by shielded metal-arc welding, selected because production quantity was low (Example 11)

Safety

Invisible ultraviolet and infrared rays emitted in shielded metal-arc welding can injure unprotected eyes and skin. Therefore, protection for the eyes and skin is mandatory.

The best protection for the face and eyes is provided by a helmet that covers the face and contains a slit-type opening covered by a filtered lens. The optimum shade of the lens varies for different welders. It should be dark enough so that the arc can be viewed without discomfort, but not so dark that visibility during welding is impaired. The following shade numbers for use with specific electrode sizes are suggested: No. 10 for electrode sizes of $\frac{1}{16}$ to $\frac{5}{32}$ in.; No. 12 for sizes of $\frac{3}{16}$ to ¼ in.; and No. 14 for $\frac{5}{16}$-in. and ⅜-in. electrodes.

Protective clothing must be fire resistant, and heavy enough to prevent passage of harmful rays. Heavy gloves should be worn to protect hands from harmful rays, and to prevent burns. Safety shoes should also be worn. The welding area should be isolated by curtains or shields, for protection of persons in the vicinity.

During deslagging of welds, helmets or safety glasses should be worn to protect eyes from flying particles.

The welding area must be adequately ventilated, because heavy concentrations of smoke and fumes are generated. Arc welding also produces ozone, which is another reason for providing good ventilation. When welding is done in small, confined areas, such as inside a tank, an external air supply furnished by use of a mask or special helmet may be required. In addition, a second person should be stationed at the tank manhole to provide assistance to the welder if necessary.

Special ventilation is required when metals coated with copper, zinc, lead or cadmium are welded, because fumes from these metals are toxic.

Precautions in installing and operating the electrical components used in shielded metal-arc welding are the same as those for other electrical devices with similar output and voltage capacities. Grounding should be solid.

Rules and regulations for installation and operation of welding equipment vary among states. Therefore, the State Industrial Commission and local governments should be consulted on applicable safety regulations before equipment is installed.

For detailed information on the safety practices discussed above, and on other precautions, safe practices, contaminants and hazards in welding, the reader is referred to "Safety in Welding and Cutting", ANSI Z49.1, American National Standards Institute.

Shielded Metal-Arc Welding of Metals Other Than Low-Carbon Steel

As stated earlier, shielded metal-arc welding is commonly done on many metals other than low-carbon steel. Table 16 lists the examples elsewhere in this volume that describe shielded metal-arc welding of other metals.

Table 16. Examples of Shielded Metal-Arc Welding Presented Elsewhere in This Volume

Metal welded	Example number	Subject of example
Low-carbon steel	12, 13, 22, 23, 27-31	Shielded metal-arc vs flux-cored arc welding
	69	Comparison of costs for four welding processes
	70-75	Shielded metal-arc vs submerged-arc welding
	76	Welding conditions for three processes
	104	Comparison of costs and welding conditions, shielded metal-arc vs gas metal-arc welding
	107-120	Comparison with gas metal-arc welding (production rates and welding conditions)
	152	Hard facing a plate
Medium-carbon steel	149, 150, 155	Hard facing selected surfaces
	181	Welding heavy channel sections back-to-back
Alloy steel	148	Hard facing an austenitic manganese steel
	198	Conditions for welding 5145 steel to 1020 steel
	208, 209	Conditions for welding various alloy steels
	211	Welding of manganese steel to alloy steel
	216, 218	Shielded metal-arc vs gas metal-arc welding
	220	Welding 3½% nickel steel pipe
	223	Weld porosity, using 2% Mn steel electrodes
Stainless steel	196, 210	Conditions for welding stainless to Cr-Mo steel
	244, 269	Conditions for welding type 347 stainless pipe
Tool steel	163, 206	Repair welding of cracked and worn dies
	165, 166	Hard facing of cutting edges on shear blades
Cast steel	199	Welding of cast steel to low-carbon steel
	204	Welding for repair of casting defects
	267	Joining of stainless steel castings
Gray iron	229, 230	Welding to repair cracks and casting defects
	231, 233	Welding of gray iron to low-carbon steel
	232	Conditions for joining of two castings
Ductile iron	234	Repair of machining and casting defects
	235	Conditions for joining of two castings
Malleable iron	238	Welding of malleable iron to low-carbon steel
Heat-resisting alloy	284	Repair of a defect in a Thermalloy B casting
Copper alloy	336	Welding aluminum bronze to low-carbon steel
	338	Butt welding alloy 715 (copper nickel) pipe
Nickel alloy	354	Welding Monel to nickel-plated steel pipe
	356	Welding Monel to Monel and to low-carbon steel

Flux-Cored Arc Welding

*By the ASM Committee on Gas Metal-Arc Welding and Flux-Cored Arc Welding of Steel**

FLUX-CORED ARC WELDING is a process in which the heat for welding is produced by an arc between a tubular consumable electrode wire and the work metal, with shielding provided by gas evolved during combustion and decomposition of a flux contained within the tubular electrode wire, or by the flux gas plus an auxiliary shielding gas. Thus, there are two major versions of the process: one that uses both an auxiliary shielding gas (usually carbon dioxide) and shielding obtained from the flux core of the electrode; and the self-shielding method, which depends for shielding on combustion and decomposition of flux-core compounds.

Both methods of flux-cored arc welding are closely related to other arc welding processes. The method that uses an auxiliary gas shield is similar to gas metal-arc welding, which employs a solid consumable electrode and depends on an externally applied gas shield for protecting the arc and molten metal from contamination by the atmosphere. The self-shielding method is more closely related to shielded metal-arc welding, which also depends on the combustion and decomposition of a solid flux to provide the gaseous shield. In shielded metal-arc welding, the flux is on the outside of the electrode, which limits the form of the electrode to a straight length (a "stick electrode"), whereas in flux-cored arc welding, the flux is inside a tubular electrode, which can be coiled and supplied to the arc as a continuous wire. (For a size comparison, see the bottom row in Fig. 5.)

Applicability

Applications of the two methods of flux-cored arc welding overlap considerably. However, the specific characteristics of each process make it suitable for different operating conditions.

Flux-cored arc welding with auxiliary gas shielding is used mainly for welding carbon and low-alloy steels and has been used successfully for welding stainless steels. The method is applicable to semiautomatic work (manually manipulated electrode holder) and to the various machine and automatic welding procedures (in which the electrode holder is held mechanically). It is also adaptable to arc spot welding.

Originally, flux-cored arc welding with auxiliary gas shielding was restricted to welding in the flat and horizontal positions, because tubular electrode wires were available only in relatively large diameters. With these large-diameter wires, the welder was unable to control the weld puddle when welding in the vertical and overhead positions. This position restriction no longer holds, partly because small-diameter electrode wires (as small as 0.035 in. in diameter) have become available and partly because electrode-wire compositions that are better suited to out-of-position welding have been developed. Now, flux-cored arc welding with auxiliary gas shielding is an all-position process. It is applicable to a wide range of work-metal thicknesses, beginning with metal as thin as $\frac{1}{16}$ in.

Because of the protection offered by auxiliary gas shielding, a spray-type arc, at high current density, can be used, which results in maximum joint penetration. An arc producing globular transfer and a short-circuiting arc can also be used. The latter types of arcs are produced at lower current density and result in shallower penetration, and are therefore better suited to the welding of thin sections and to out-of-position welding. (All three types of arc are shown in Fig. 2, page 79, in the article on Gas Metal-Arc Welding.)

Joints made by flux-cored arc welding with auxiliary gas shielding meet the quality requirements of many codes; radiographs of welds show that sound deposits that meet exacting face and root bend tests can be produced. In many applications, flux-cored arc welding with an auxiliary gas shield is competitive with gas metal-arc welding; in other applications, it is competitive with submerged-arc welding.

A disadvantage of flux-cored arc welding is that the deposit is covered with solid slag, much the same as, although thinner than, the deposit made by shielded metal-arc welding. This slag is usually removed between welding passes. (With certain flux-cored electrodes, slag removal is not required on two-pass horizontal fillet welds.) Consistency and adherence of the slag depend on the composition of the electrode wire. Some slag coverings crack during cooling and can be easily removed with a wire brush; others adhere firmly and must be broken up with a deslagging hammer to permit removal by wire brushing.

Flux-Cored Arc Welding With Self Shielding. This method of flux-cored arc welding has become popular for many applications, mainly because of the simplicity of operation that results from the absence of the equipment necessary for gas shielding. In addition, the electrode holder is simpler than that required for use with auxiliary shielding gas. Because the self-shielding method does not penetrate as deeply as the auxiliary-gas-shielded method, it can be used under conditions of poor fit-up to better advantage. The self-shielding method is used mainly for welding carbon steels, but has been used successfully for welding some low-alloy steels, and at least one company has developed flux-cored electrode wires for welding austenitic stainless steels.

The self-shielding method can be used for out-of-position welding by selection of a small-diameter electrode wire of suitable composition, just as for the auxiliary-gas-shielded method. The range of work-metal thickness is the same for both methods.

Flux-cored arc welding without an auxiliary gas shield is not suited to a spray-type arc. Because metal is transferred from the outside of the electrode to the weld puddle, protection from oxidation in this area is minimum without an auxiliary gas shield. When a fine spray is developed, the total surface area of the metal particles is large, which results in excessive oxidation. Therefore, the self-shielding method should be operated with globular or short-circuiting metal transfer.

The quality of welds made by self-shielding flux-cored arc welding is gen-

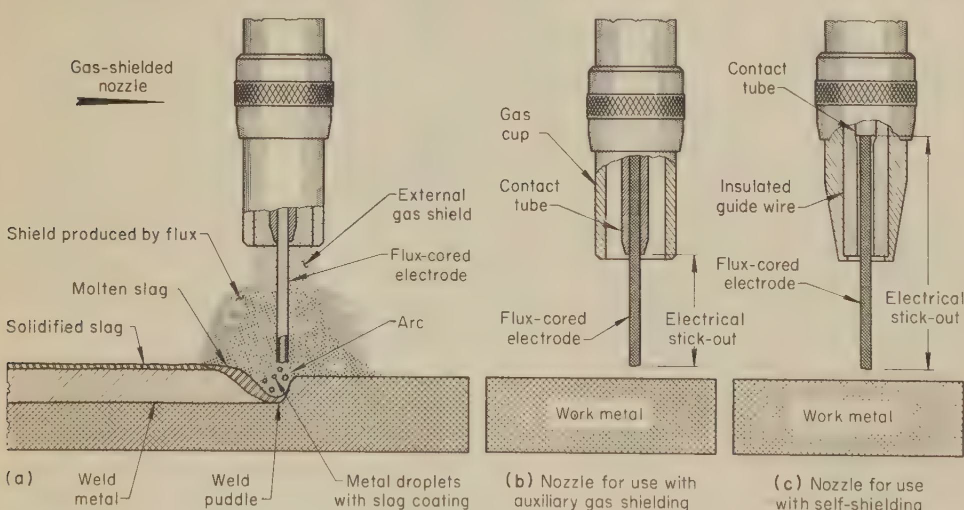


Fig. 1. (a) *Operating principles for flux-cored arc welding with auxiliary gas shielding;* (b) and (c) *nozzles for auxiliary-gas-shielded and for self-shielding methods of flux-cored arc welding (note difference in lengths of electrical stickout).*

*For committee list, see page 78. More than half of the examples presented in this article were contributed by members of other Metals Handbook welding committees. A total of 13 examples of flux-cored arc welding appear in other articles in this volume, as recorded in the table at the end of this article (page 45).

erally lower than that of welds made with auxiliary gas shielding. The main cause of lower weld quality is the greater contamination of the weld deposit by the atmosphere during welding; another cause is the presence of gas-forming and deoxidizing elements in the flux core of the electrode wire. The mechanical properties adversely affected are ductility and impact strength, particularly at low temperature. Some codes do not permit the use of self-shielding flux-cored arc welding for steels having a yield strength greater than 42,000 psi.

A major advantage of the self-shielding method is that it can be used in a draft, as can shielded metal-arc welding — although such practice is not recommended for either process.

Fundamentals of the Process

Basic equipment requirements for flux-cored arc welding are essentially the same as for gas metal-arc welding — that is, a power supply, a wire feeder to advance the electrode wire as it melts to form the weld deposit, an electrode holder, and, when appropriate, a means of supplying auxiliary shielding gas. These components are shown in Fig. 1 of the article on Gas Metal-Arc Welding (see page 78).

Likewise, the arc characteristics that can be obtained in flux-cored arc welding are essentially the same as those in gas metal-arc welding. The spray arc, the globular type of transfer, and the true short-circuiting arc are shown in Fig. 2 of the article on Gas Metal-Arc Welding (see page 79).

Principles of Operation. The flux-cored wire is the main difference between gas metal-arc welding and flux-cored arc welding with an auxiliary gas shield (see Fig. 1a). The flux core provides a molten slag that covers the weld metal, and a gas that assists in shielding of the arc. The necessary equipment, including the electrode holder, is essentially the same for both of these processes.

Aside from the use or nonuse of auxiliary shielding gas, the self-shielding and auxiliary-gas-shielded methods differ mainly in the type of electrode holder used and in the length of electrical stickout. As illustrated in Fig. 1(b), with the type of electrode holder used with the auxiliary-gas-shielded process, the contact tube extends nearly to the end of the gas cup, so that the electrical stickout (distance from the end of the contact tube to the weld puddle) is nearly the same as the visible stickout (distance from the end of the gas cup to the weld puddle). Electrical stickout is the more meaningful term and is generally what is referred to when the word "stickout" is used without qualification. In many electrode holders, the distance from the end of the contact tube to the end of the gas cup is ⅜ in. or more, about the same as for gas metal-arc welding. Electrical stickout is commonly about ¾ to 1 in.

For the self-shielding method, a much greater electrical stickout is used — 2½ in. or more — as indicated in Fig. 1(c). Because no provision need be made for shielding gas, the space at the end of the electrode holder can be occupied

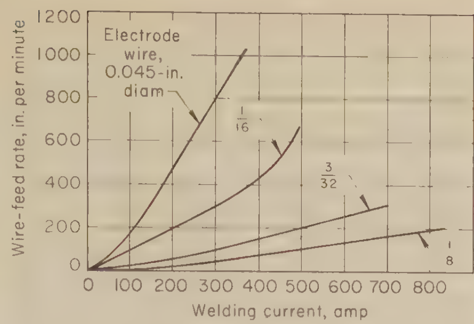


Fig. 2. Interrelation of wire-feed rate and welding current for four sizes of electrode wire, using carbon dioxide shielding gas

by an insulated wire guide, which prevents the wire from touching the end or nozzle portion of the electrode holder. The use of a longer electrical stickout allows a higher deposition rate, since the electrode wire is preheated more because of the greater distance along which the welding current flows through the electrode.

Power Supply

Alternating current is seldom used for welding with flux-cored electrode wires. Direct current supplied by a rectifier, motor-generator, or engine-driven generator and operated with reverse polarity is generally used; straight polarity is also used, although only to a limited extent.

Either of two general types of power supply can be employed: the constant-current type (drooping voltage characteristic), such as is commonly used for shielded metal-arc welding, or the constant-voltage type, originally developed for use with gas metal-arc welding. When a constant-current power supply is employed, it is usually matched to an arc-voltage-sensing electrode-wire feeder. A constant-voltage power supply, which is the type most often used for flux-cored arc welding, should be employed only for continuous-feed electrode-wire processes. The electrode wire is fed into the arc at a specific rate, and it automatically draws the amount of current from the constant-voltage power supply required to maintain the preset arc voltage. If wire-feed rate is increased, current increases and, of course, deposition rate increases. This system is simple to control. Figure 2 shows the interrelation of wire-feed rate and welding current for four common sizes of flux-cored electrode wire.

Various models and sizes of constant-voltage power supplies are available, most of which incorporate slope and inductance control. Power supplies that can be varied in slope and inductance are more versatile and can be used for a wide variety of conditions.

For further discussion of power supplies suitable for flux-cored arc welding and gas metal-arc welding, see page 80, in Gas Metal-Arc Welding.

Electrode Holders

Electrode holders for auxiliary-gas-shielded flux-cored arc welding are similar to those used for gas metal-arc welding. Various sizes, ratings and styles, suitable for both semiautomatic and automatic welding, are available. Both air-cooled and water-cooled electrode holders are made. Air-cooled holders depend on radiation of heat to the surrounding air for cooling, although the shielding gas, which is quite cold as it passes through the holders, helps to cool them. Choice of holder depends largely on the welding current and shielding gas used. When current is 500 amp or more, a water-cooled electrode holder is usually employed. Some welders prefer water-cooled holders when using welding currents of less than 500 amp.

Three types of electrode holders are shown on page 82, in the article on Gas Metal-Arc Welding, together with additional discussion of electrode holders for use with a shielding gas.

Electrode Holders for the Self-Shielding Method. The same electrode holder can be used for self-shielding flux-cored arc welding as is used for the auxiliary-gas-shielded method, by not making the gas connections. Ordinarily, the electrode holder requires minor modification for use without auxiliary gas shielding — for example, a longer stickout is used (Fig. 1). Actually, it is uncommon to use the same electrode holder for self-shielding welding as for welding with an auxiliary gas shield. Electrode holders of various sizes and styles are made especially for self-shielding flux-cored arc welding. Typical hand-manipulated and mechanically manipulated electrode holders are shown in Fig. 3.

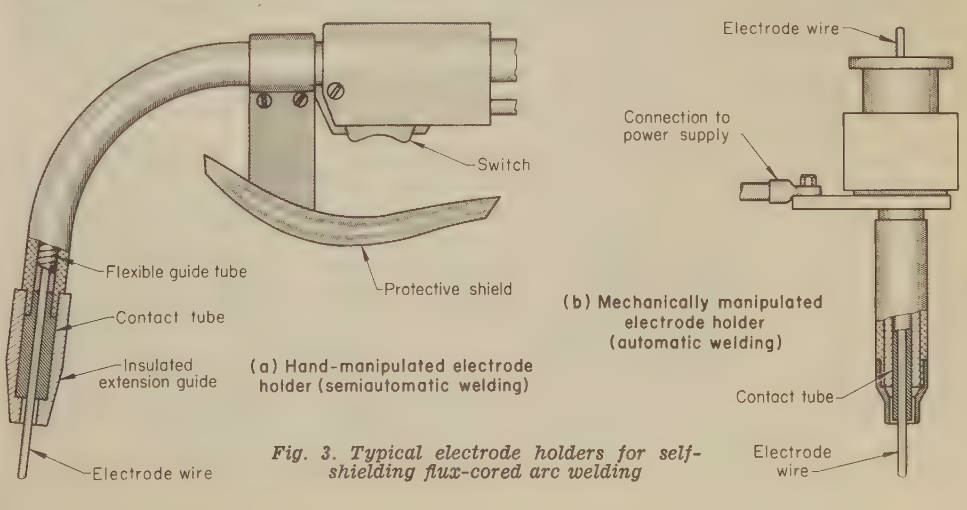


Fig. 3. Typical electrode holders for self-shielding flux-cored arc welding

Cooling systems for water-cooled electrode holders are of two types. In the most widely used system, water is obtained from a pressurized fresh water source, passed through the electrode holder, and discharged. If the welding location is not near a water line, a tank about the size of a common 200-cu-ft compressed-gas cylinder and an electric-motor-driven pump to recirculate the water are employed. This system can be mounted on the portable truck that holds the other welding equipment.

Wire-Feed Systems

Because constant-voltage power supplies are used most often for both methods of flux-cored arc welding, a constant wire-feed system is needed (see section on Power Supply, page 25).

A push-type wire-feed system is universally employed for both methods, for three reasons: (*a*) electrode-wire diameter is fairly large — the smallest size made is 0.035 in. in diameter and the smallest size commonly used is 0.045 in. in diameter; (*b*) because all electrode wires are made of steel and are stiff, feeding is greatly facilitated with a push-type feeder; and (*c*) because the feed mechanism is not located in the electrode holder, the holder weighs less and is easier to manipulate.

The system used for feeding flux-cored wire is similar to that used for feeding solid wire (see the section dealing with wire-feed systems on page 82 in "Gas Metal-Arc Welding").

Push-Type Systems. In a push-type wire-feed system, the electrode wire is pulled from a reel by feed rolls and pushed through a flexible wire conduit to the electrode holder and thence into the arc. A constant rate of feed is mandatory in a constant-voltage system, but the feed rate must be capable of adjustment in order to obtain the required welding current.

A four-roll feeder is shown in Fig. 4(a). In this feeder, all four rolls are driven. Push-type feeding systems vary considerably among manufacturers. Some have only two rolls — one driven roll and one pressure roll. The design must ensure that the roll speed and pressure can be varied and that the rolls can be changed quickly.

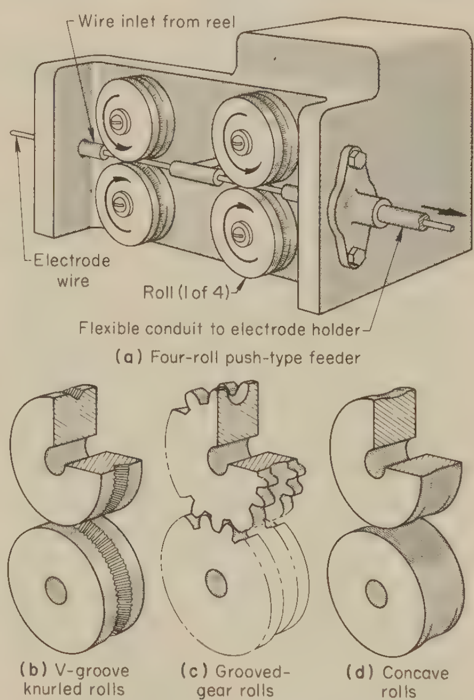
Push-type wire-feed systems are coupled electrically to the power supply. For convenience, wire feeders are most often mounted on the power supply, although they have been separated from the power supply by distances up to 200 ft. They can be mounted on overhead jib cranes or booms, thus allowing the welder to cover a large area, and they can be located on the shop floor, on the ground, or on overhead scaffolding.

Table 1. Composition Requirements for Weld Metal From Flux-Cored Electrodes (AWS A5.20-69) (a)

AWS classification	Weld-metal composition, %, max(b) Mn	Si	Ni	Al
E60T-7	1.50	0.90	0.50	1.8
E60T-8	1.50	0.90	0.50	1.0
E70T-1	1.75	0.90	0.30(c)	...
E70T-4	1.50	0.90	0.50	1.8
E70T-5	1.50	0.90	0.30(c)	...
E70T-6	1.50	0.90	0.80	...

(a) Composition is not specified for E70T-2, E70T-3 or E70T-G electrodes. Also, carbon, phosphorus and sulfur are not specified for any flux-cored electrodes. (b) 0.20 Cr, 0.30 Mo, and 0.08 V may be present, but are not included intentionally. (c) May be present, but is not included intentionally.

A given joint may require the use of electrodes of two different sizes. A typical application would call for a root pass to be made by gas metal-arc welding, employing a very-small-diameter solid wire and for the weld to be completed by flux-cored arc welding, using a larger-diameter wire. A wire-feed system capable of supplying electrode wire to either of two electrode holders is available for such applications. This type of wire feeder has two electrode-holder-and-cable assemblies and two sources of wire. By actuating a switch and picking up the appropriate electrode holder, the welder can select gas metal-arc welding or flux-cored arc welding. A single power supply is used. With some models, two motors are employed for driving the two wire feeders, and in other models, the two wire feeders are driven by a single ¼-hp motor and a dual drive.



(a) Four-roll push-type feeder, in which all rolls are driven. (b) V-groove knurled feed rolls, used for electrode wire of medium to large diameter. (c) Grooved-gear feed rolls, used for soft flux-cored electrode wire. (d) Concave, smooth-face rolls, used for small-diameter wire.

Fig. 4. Electrode-wire-feed system and three designs of feed rolls

Feed Rolls. Because of their tubular construction, flux-cored electrode wires are easily flattened. As a result, the design of the feed rolls is critical. Various types of grooved, grooved and knurled, and concave rolls have been used successfully (see Fig. 4).

It is important to select rolls that are compatible with the wire size; rolls must be changed when there is an appreciable change in wire diameter. The V-groove knurled rolls shown in Fig. 4(b) are commonly used for feeding wires with a diameter greater than about 1/16 in. This type of roll is lightly knurled so that the wire can be fed without slipping and without the use of excessive pressure.

Another type of feed roll, shown in Fig. 4(c), is used in a two-roll wire feeder. Each roll is a gear having a round groove with the same radius as the wire to be fed. The groove is cut into both rolls but is cut only part way through the tooth. The grasp of the wire is by the relatively flat surface of the groove. The advantage in this type of roll is that it does not mar the surface of soft flux-cored wires.

Small-diameter wires (for example, 0.045 in.) are less easily flattened than are larger-diameter wires, and simple concave rolls without knurls, as shown in Fig. 4(d), are usually satisfactory.

Maintenance of Feed Systems. Wire-feeding mechanisms require scheduled regular maintenance to ensure a smooth and constant delivery of wire to the arc. The guides, feed rolls, and reels must be properly aligned and adjusted, and the wire conduit must be cleaned at regular intervals, normally before a fresh reel of wire is put into service. This should be done by removing the wire and blowing clean air or shielding gas through the conduit.

Flux-Cored Electrode Wires

Flux-cored electrode wire consists of a low-carbon steel sheath surrounding a core of fluxing and alloying material.

Manufacture of flux-cored electrode wire is a specialized and precise operation. Most flux-cored electrode wire is made by passing low-carbon steel strip through contour-forming rolls that bend the strip into a U-shape cross section. The U-shape product is then filled with a measured amount of granular core material (flux) by passing it through a filling device. Next, the flux-filled U-shape strip passes through closing rolls that form it into a tube and tightly compress the core materials. The tube is then pulled through drawing dies that reduce its diameter

Table 2. Shielding and Current Type for Flux-Cored Electrodes, and Mechanical-Property Requirements for Weld Deposits (AWS A5.20-69)

AWS classification	Shielding gas	Current and polarity	X-ray	Minimum properties of weld metal: Tensile strength, psi	Yield strength, psi	Elongation in 2 in., %	Charpy V-notch impact, ft-lb
E60T-7	None	Dcsp	Required	67,000	55,000	22	(a)
E60T-8	None	Dcrp	Required	62,000	50,000	22	20 at 0 F
E70T-1	CO_2	Dcrp	Required	72,000	60,000	22	20 at 0 F
E70T-2	CO_2	Dcrp	...	72,000	(a)	(a)	(a)
E70T-3	None	Dcrp	...	72,000	(a)	(a)	(a)
E70T-4	None	Dcrp	Required	72,000	60,000	22	(a)
E70T-5	None; CO_2	Dcrp	Required	72,000	60,000	22	20 at −20 F
E70T-6	None	Dcrp	Required	72,000	60,000	22	20 at 0 F
E70T-G	(b)	(b)	...	72,000	60,000(c)	22(c)	(a)

(a) Not required. (b) Not specified. (c) For multiple-pass electrodes.

and further compress the core materials. The drawing operation secures the core materials inside the tube. The electrode may or may not be baked during or between drawing operations, depending on its type.

Additional drawing operations are performed to produce different sizes of electrode wire. The standard sizes are 0.045, 1/16, 5/64, 3/32, 7/64, 1/8 and 5/32 in. in diameter (0.035-in.-diam wire is available in limited quantities). The 3/32-in.-diam wire is the size most widely used; 5/64-in. wire is also popular.

The finished electrode wire is wound into a continuous coil or onto spools, as required. Various standardized methods of packaging are in use; most electrode wire is wound into 25-lb and 50-lb spools and 60-lb coils, but other sizes and forms are used on occasion. The spools and coils are placed in moistureproof plastic bags and then in shipping boxes, to ensure that deterioration does not occur.

Functions of the compounds contained in the core (see the Appendix to this article) are similar to those in the covering on the stick electrodes used for shielded metal-arc welding, which are:

1 To act as deoxidizers or scavengers to help purify the weld metal and produce a sound deposit
2 To form slag to float on the molten weld metal and protect it from the atmosphere during solidification
3 To act as arc stabilizers to produce a smooth welding arc and reduce weld spatter
4 To add alloying elements to the weld metal to increase weld strength and to provide other required weld-metal properties
5 To provide shielding gas.

Construction. Several styles of flux-cored electrodes are shown in cross section in Fig. 5. In the three styles shown in the top row of the illustration, the steel portion of the electrode comprises about 75 to 85% of the total weight and about 75% of the cross-sectional area of the electrode.

The amount of flux contained in the core of a flux-cored electrode is less than is used on flux-covered stick electrodes of comparable size (see bottom row in Fig. 5), because the covering on stick electrodes must contain binders to keep the covering adherent and continuous, and constituents that enable it to be extruded.

Comparison of a typical flux-covered electrode with a typical flux-cored electrode shows the percentage of steel in each to be as follows:

	Flux-covered E7016	Flux-cored E70T-1
Steel by area	45%	75%
Steel by weight	76%	85%

Metal transfer from consumable electrodes across an arc is by the spray, globular or short-circuiting mode.

On cored electrodes, the molten droplets form on the periphery (or sheath) of the electrode. A droplet forms and is transferred, and then another droplet forms at another location on the metal sheath and is transferred. The core material appears to transfer to the weld-puddle surface independently.

At low current densities, the droplets are larger than at high current densities. For instance, the transfer from a 3/32-in.-diam flux-cored electrode was observed at 350, 425 and 550 amp, respectively. At 550 amp, it appeared that some metal was being transferred by spray. Large droplets, which formed at lower current densities, caused splashing as they entered the weld puddle, thus increasing the amount of visible weld spatter. This explains why there is less visible spatter, the arc appears smoother, and deposition efficiency is higher when current density is high.

Classification of Electrodes. Nine types of flux-cored electrodes are covered by AWS specification A5.20-69, although the manufacturers of electrodes produce numerous other types that have not been classified by the American Welding Society. The composition requirements for weld metal deposited from six standard electrodes are given in Table 1. Note that no carbon content is specified. The carbon content of an actual weld will depend largely on the carbon in the base metal, somewhat on the carbon in the electrode, and to a slight extent on the shielding gas, if carbon dioxide gas is used (for typical carbon contents of weld metal, see Tables 21, 22, and 25 to 29 in the Appendix of this article). Additional information on nine electrodes, including use and nonuse of auxiliary shielding gas, inspection requirements for deposits, and minimum mechanical properties of deposits, is given in Table 2 and in the Appendix.

The classification system for flux-cored electrodes follows the system established for gas metal-arc electrodes. For example, in the designation E70T-1, E indicates an electrode; 70 indicates a minimum as-welded tensile strength of 70,000 psi; T indicates a tubular-type electrode; and 1 indicates a specific composition of the deposited weld metal, use of auxiliary shielding gas, and a usability factor.

Characteristics of specific electrode wires are summarized below, including properties of weld deposits. (See also the Appendix, pages 40 to 45.)

E60T-7 electrode wires are used without auxiliary gas shielding for single-pass and multiple-pass welding in the flat and horizontal positions. They are used with straight-polarity direct current, resulting in shallow joint penetration. Weld deposits have low sensitivity to cracking and good notch toughness.

E60T-8 electrode wires are used without auxiliary gas shielding, and with reverse-polarity direct current. Tensile strength and yield strength of deposits are generally lower than for deposits made with E60T-7, but notch toughness is high (see Table 2).

E70T-1 electrode wires are intended to be used with auxiliary gas shielding, for single-pass and multiple-pass welding in the flat position and for horizontal fillet welds. For some electrodes in this classification, joints must be free of oil, excessive oxide, and scale, so that welds of radiographic quality can be obtained. A quiet arc, high deposition rate, low spatter loss, a flat to slightly convex bead, and easily controlled and removed slag are characteristics of these electrodes. Weld deposits have good impact properties.

E70T-2 electrode wires are also used with auxiliary gas shielding. They are designed primarily for single-pass welding in the flat

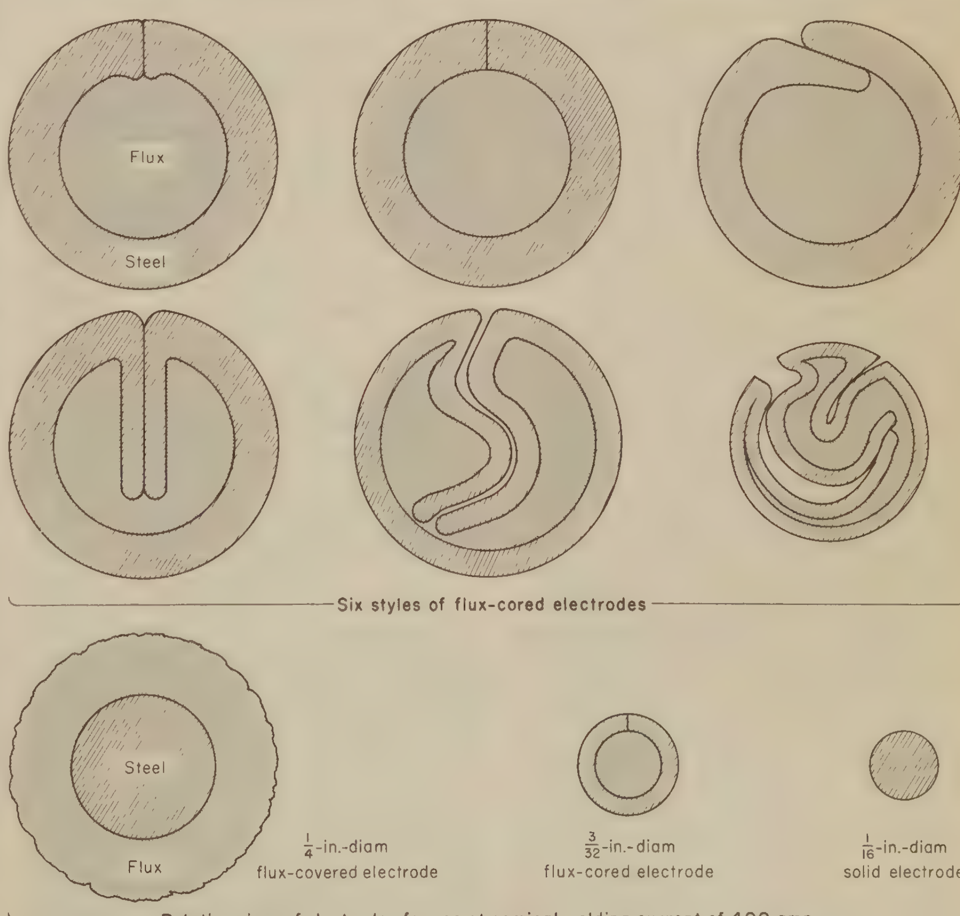


Fig. 5. Several styles of flux-cored electrodes, and size comparison of flux-covered, flux-cored and solid metal electrodes for use at the same nominal welding current

position and for horizontal fillet welds. However, multiple-pass welds can be made when the weld beads are heavy and appreciable admixture of base and filler metals occurs. These electrodes can be used for welding steel that has heavier mill scale, rust, or other foreign material on the surface than can be tolerated by some electrodes of the E70T-1 classification, and they will still produce welds that will pass radiographic inspection. The arc characteristics and deposition rates of the E70T-2 electrode wires are similar to those of the E70T-1 electrodes.

E70T-3 electrode wires are used without auxiliary gas shielding and are intended primarily for depositing single-pass welds at high speed in the flat and horizontal positions on relatively thin steel. These electrodes should not be used to weld heavy sections or for applications requiring multiple passes.

E70T-4 electrode wires are used without auxiliary gas shielding for single-pass and multiple-pass welding in the flat and horizontal positions. Due mainly to shallow joint penetration, the weld deposits have low sensitivity to cracking.

E70T-5 electrode wires are intended primarily for flat fillet or groove welds, with or without auxiliary gas shielding. Horizontal fillet welds can be satisfactorily made, but at lower deposition rates than are obtainable for flat groove welds. Welds made using auxiliary gas shielding have better quality than those made with no auxiliary gas shielding. E70T-5 electrodes can be used in single-pass and multiple-pass applications, with minimum surface preparation. These electrodes give globular transfer, shallow penetration with the self-shielding method and medium to deep penetration with the auxiliary-gas-shielded method, and a slightly convex weld bead, and they produce a thin, easily removed slag. Weld deposits have good impact properties (see Table 2).

E70T-6 electrode wires are generally similar to those of the E70T-5 classification, except that they are intended for use without auxiliary gas shielding.

The E70T-G classification covers tubular electrodes that are not included in the preceding classes. They may be used with or without auxiliary gas shielding, for multiple-pass or single-pass welding. Welds are not required to meet composition, radiographic inspection, or impact-property requirements; however, they are required to have minimum tensile strength of 72,000 psi, minimum yield strength of 60,000 psi, and minimum elongation of 22% in 2 in.

Flux-cored electrode wires are considered to be low-hydrogen electrodes, because the materials used in the cores do not contain hydrogen. However, certain of the materials are hygroscopic and may absorb moisture when exposed to a high-humidity atmosphere. Electrode wires are therefore packaged in a moisture-proof bag with a desiccant. It is recommended that, after removal from their original container, flux-cored electrode wires be treated in the same manner as low-hydrogen flux-covered electrodes are treated after removal from their original container (see page 7 in the article on Shielded Metal-Arc Welding in this volume).

A special series of flux-cored arc welding electrode wires is available for welding high-strength structural steels and high-strength alloy steels (see the article on Arc Welding of Alloy Steels, which begins on page 199). Electrode wires of this series are for use with auxiliary gas shielding. The core of the electrode wire carries alloying elements in addition to the normal gas-formers, fluxing elements, and deoxidizers. The alloying elements in the core melt in the arc and mix with the molten low-

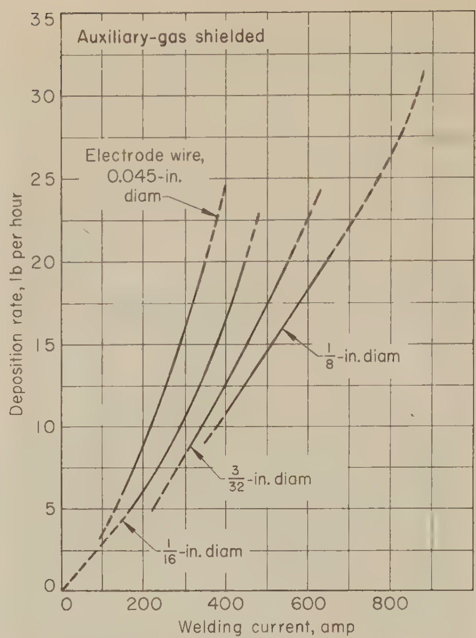


Fig. 6. Effect of welding current and electrode-wire diameter on deposition rate. The solid part of each curve indicates the normal current range for that size of electrode.

carbon steel outer sheath to produce the required composition of deposited weld metal. One major advantage of flux-cored electrode wires over solid electrodes is that the cored wires can readily be made to match virtually any base-metal steel composition.

Shielding Gases

Gases used for auxiliary-gas-shielded flux-cored arc welding can be the same as those used for gas metal-arc welding, which include carbon dioxide, 98% argon with 2% oxygen, and 75% argon with 25% carbon dioxide, but almost always carbon dioxide is used alone. The chemical reactions of carbon dioxide with the carbon steel base metal and with the cored electrodes make it desirable as a shielding gas. In addition, carbon dioxide is less costly than the mixtures containing argon, based on the cost of gas per pound of weld metal deposited.

Characteristics of Carbon Dioxide. At room temperature, dry carbon dioxide is an inactive gas that has no adverse effect on the metals with which it comes in contact; but at the high temperature of the welding arc, it dissociates, in the following reaction:

$$2CO_2 \leftrightarrows 2CO + O_2$$

This dissociation leaves considerable oxygen available in the arc to oxidize metallic elements. Molten iron, for example, reacts with carbon dioxide to produce iron oxide and carbon monoxide, as follows:

$$Fe + CO_2 \leftrightarrows FeO + CO$$

The oxidizing characteristics of carbon dioxide have been considered in the development of flux-cored electrodes, and deoxidizing materials are added to the flux core to compensate for it. Some of the carbon monoxide produced during the reaction between iron and carbon dioxide may dissociate to carbon and oxygen. The carbon released by this reaction is available to dissolve in the weld metal, thereby increasing the carbon content.

Depending on the carbon content of the base metal and of the electrode, a carbon dioxide atmosphere may be either carburizing or decarburizing. Carbon content in the weld deposit usually ranges between 0.05 and 0.12%. If the carbon content of the electrode metal and of the base metal is lower than 0.05%, the weld metal will pick up carbon from the carbon dioxide shielding atmosphere. Conversely, if the carbon content of the electrode metal and of the base metal is greater than 0.12%, the weld metal may lose carbon. This loss of carbon can occur as follows:

$$FeO + C \leftrightarrows Fe + CO$$

When the above reaction occurs, carbon monoxide gas can be trapped in the weld deposit, where it may produce porosity. The reaction is avoided by keeping the level of the deoxidizing elements in the core of the electrode sufficiently high.

In general, joint penetration with flux-cored arc welding with carbon dioxide shielding is much greater than with shielded metal-arc welding using low-hydrogen iron powder electrodes, but not as deep as with gas metal-arc welding using solid electrode wire and carbon dioxide shielding, operating in the same range of welding current.

Containers for Carbon Dioxide. Carbon dioxide is available in cylinders or in bulk. The most widely used container is the ICC-approved high-pressure steel cylinder. Cylinders containing carbon dioxide are always labeled "CO_2", and for welding applications they should be labeled "Welding Grade".

A cylinder from which no gas has been drawn contains, at 70 F, gaseous carbon dioxide and liquid carbon dioxide. The gas occupies about one-third of the volume of the cylinder, and when gas is withdrawn, liquid vaporizes and maintains the gas pressure. When all the liquid carbon dioxide has been vaporized, the pressure starts to fall. Originally, the weight of liquid carbon dioxide is about 90% of the weight of the contents of a cylinder. In order to determine how much remains in a partly used cylinder, the cylinder should be weighed (pressure is not a reliable indication of cylinder content). The tare weight of the (empty) cylinder is usually stenciled on the cylinder neck. At 70 F, 8.47 cu ft of carbon dioxide weighs 1 lb at standard pressure.

As the pressure drops from cylinder pressure to discharge pressure in the regulator, carbon dioxide absorbs a considerable amount of heat. If the flow rate is too high, the heat absorption can cause freezing of the regulator and flowmeter, which interrupts gas flow. Heaters are available that will prevent regulator freeze-up. Excessive rates of gas flow also can result in the withdrawal of liquid carbon dioxide from the cylinder.

A positive pressure should always be maintained in the cylinder (the valve should be closed before the cylinder is removed from service) to keep moisture or other contaminants from backing into the cylinder. Carbon dioxide cylin-

ders should always be kept in an upright position and held firmly in place when in use at the welding station. If it is placed in a horizontal position, carbon dioxide will be drawn off as liquid instead of as gas.

Siphoned-tube cylinders require a heater to transform the liquid to gas. Nonsiphoned-tube cylinders operating at flow rates greater than 35 cu ft per hour should be manifolded to reduce flow rate and prevent freezing.

Flow rate for carbon dioxide shielding gas is at least 30 cu ft per hour for most welding applications. When welding outdoors or at a drafty site, the operation should be protected by a wind shield, and the flow rate should be increased to 50 cu ft per hour.

Purity. Welding-grade carbon dioxide is required. The purity of the gas is based on the percentage of moisture present, which is indicated by a dew-point temperature of −40 F (or −40 C). At −40 F (or −40 C) dew point, the percentage of moisture by weight is 0.0066, or 66 parts per million.

Equipment Installations

Support equipment required for flux-cored arc welding is about the same as for gas metal-arc welding. Less equipment may be needed if no auxiliary gas shielding is applied. It can range from completely portable to large, highly mechanized stationary setups. Support equipment is dealt with in the section on Equipment Installations, page 89, in the article on Gas Metal-Arc Welding in this volume.

Holding and Handling of Workpieces

Jigging and fixturing requirements for flux-cored arc welding are the same as those for gas metal-arc welding. Holding and handling devices are discussed and illustrated in the section beginning on page 90 in the article on Gas Metal-Arc Welding in this volume. Applicable techniques are discussed also in the section on Accessory Equipment in the article on Gas Tungsten-Arc Welding, and in the section on Jigs, Fixtures and Positioners in the article on Shielded Metal-Arc Welding.

The importance of positioning workpieces so that they can be welded in as flat a position as possible is no less, and may be greater, than when welding by the gas metal-arc method. In most arc welding methods, maximum efficiency is obtained when welding is done in the flat position. Flux-cored arc welding can be done in all positions, but it is generally less amenable to out-of-position welding than is gas metal-arc welding, because it usually (but not always) employs larger-diameter electrode wires and deposition rates are higher. Out-of-position welding increases production time, restricts electrode selection, requires greater skill, and may impair weld quality.

Deposition Rate

As is true for all arc welding processes, the deposition rate for flux-cored arc welding depends on the welding current and the electrode diameter. Typical relations between current and deposition rate for four different electrode-wire diameters are given in Fig. 6, which indicates for each electrode-wire diameter the current range that is normally appropriate. Deposition efficiency in flux-cored arc welding is generally high, sometimes as high as 92%.

Effects of Operating Variables

The principal operating variables that must be controlled are arc voltage, current, travel speed, and electrical stickout. The effects of changes in these variables are summarized in the paragraphs that follow:

Arc voltage variations have the following effects:

1 Excessive arc voltage results in heavy spatter and porosity.
2 Increasing the arc voltage flattens and widens the weld bead.
3 Decreasing the voltage may cause a convex bead having a ropey appearance.
4 Extremely low voltage causes the electrode to "stub" on the workpiece. The electrode dives through the molten weld puddle and strikes the unmelted base metal at the bottom of the puddle.
5 With higher current, higher voltage can be used without causing porosity. Using the highest voltage possible (without causing porosity) will result in a weld bead shape that is satisfactory for most applications.

Current variations have the following effects when arc voltage, travel speed, and electrical stickout are all held constant:

1 Excessive current produces convex weld beads, which result in waste of weld metal and poor appearance.
2 Melting rate, deposition rate, and penetration are increased by increasing the current.
3 Large-droplet transfer results from too low current, causing difficulty in maintaining a uniform weld bead.
4 Increasing the current also increases the maximum voltage that can be used without causing porosity.

Travel speed variations have the following major effects when arc voltage, current, and electrical stickout are held constant:

1 Convexity of the weld bead, with uneven edges, and shallower penetration result from too high a travel speed.
2 Slag interference and slag inclusions, together with a rough, uneven weld bead, result from too slow a travel speed.

To obtain weld beads of even contour, maintenance of uniform travel speed is essential. The welder should maintain a uniform distance between the end of the electrode and the molten slag behind the electrode.

As in all other welding processes in which the molten weld puddle is protected by slag or flux, a travel speed should be used that will produce the desired weld size and appearance by maintaining a proper relationship between the positions of the molten weld puddle and the slag that protects it.

Electrical stickout is the distance between the electrode nozzle contact tip and the workpiece (see Fig. 1). If voltage, current setting and travel speed are held constant, variations in electrical stickout have the following major effects:

1 Increasing stickout decreases the welding current; decreasing stickout increases current.
2 When stickout is increased, actual arc voltage is lowered. Lower arc voltage increases weld bead convexity and reduces the likelihood of porosity.
3 When stickout is excessive, spatter and irregular arc action will result.
4 Short stickout gives greater penetration than long stickout.
5 When stickout is too short, spatter will build up on nozzle and contact tube.

Groove Welding

Welding position, work-metal thickness, shape of the groove, and use or nonuse of backing affect procedures and techniques employed in making groove welds. Typical welding conditions for several types of grooves welded in various positions are given in Tables 3 to 7. Specific applications may necessitate considerable deviation from the practices suggested in these tables; for instance, conditions given in the examples later in this article do not always agree with those given in Tables 3 to 7. However, the data shown in these tables are based on extensive development work and should provide useful guidelines for establishing welding procedures for specific applications. For additional information on design of grooves, reference should be made to "Recommended Proportions of Grooves for Arc Welding", pages 148 to 151.

Fillet Welding

As with groove welding, procedures for fillet welding vary widely among different shops. The welding conditions shown in Tables 8 and 9 provide guidelines for several sets of conditions.

Welding position has a major influence on technique. For example, Table 8 shows that a ½-in. fillet weld can be made in two passes in the flat position, whereas Table 9 indicates that three passes are required for a ½-in. fillet weld in the horizontal position.

Angle of the electrode wire to the joint has considerable effect on the appearance of the completed weld deposit. The electrode wire should point at the bottom plate close to the corner of the joint if best bead shape is desired on horizontal fillet welds 5⁄16 in. and larger. The angle between the electrode wire and the bottom plate should be less than 45°, because with this position the molten metal is caused to wash up onto the vertical member. If root porosity occurs, it may be decreased by pointing the electrode directly into the joint and using an angle of 45° to 55°, but this may cause some weld spatter, as well as a convex weld bead. For ¼-in. and smaller fillet welds, the electrode wire should be pointed directly into the joint and at an angle to the joint about 40° above horizontal.

Multiple-Position Welding

The development of small-diameter electrode wire (0.045 in. or less) has made it possible to employ flux-cored arc welding in the vertical position, thereby extending the use of the process to building construction and tank fabrication. The desirability of using flux-cored arc welding for structural

members helped to establish conditions that meet code requirements. Typical electrode sizes, and amperage and voltage ranges are given in Table 10. These conditions apply to both groove and fillet welding.

With a choice of 1/16-in. and 5/64-in.-diam electrode wires, and using the appropriate type of flux and suitable process adjustments, welding can be done in any position.

Downhill and vertical-down welding can be done in low-cost single-pass welds. About a 60° downhill angle and 5/64 or 3/32-in. electrode wires result in maximum deposit speed, although the smaller 1/16-in. electrode can be used also. To make such deposits, stringer beads and currents in the middle to high part of the amperage range should be used. If the electrode holder is tipped in the direction of travel so that the arc force tends to hold the molten metal in the joint, the deposits will appear much more uniform. Welding should be done as fast as is possible for the desired size and shape of weld bead.

Out-of-position welding can be done if a few basic rules are followed: (*a*) do not whip or move the arc around rapidly; (*b*) do not break the arc too rapidly; (*c*) do not move out of the weld puddle too fast; (*d*) do not move too fast in any direction; and (*e*) use current in the low part of the amperage range.

Thick Sections

The high deposition rates and deep joint penetration obtainable with auxiliary-gas-shielded flux-cored arc welding have proved the process to be economical for welding sections more than ½ in. thick.

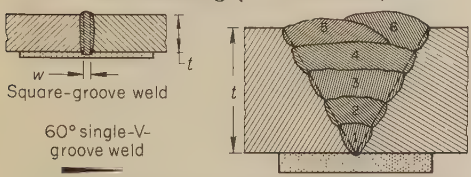
Sections ½ to ¾ In. Thick (Comparison of Processes). The two examples that follow describe practice used for, and indicate specific advantages of, auxiliary-gas-shielded flux-cored arc welding as compared with shielded metal-arc welding for sections between ½ and ¾ in. thick.

Examples 12 and 13. Advantages of Flux-Cored Over Shielded Metal-Arc Welding

Example 12 — Increased Deposition; Smaller Fillets (Fig. 7). The weldment shown in Fig. 7, consisting of two flat plates ½ in. thick and one formed plate ¾ in. thick, was originally joined by shielded metal-arc welding, using ⅜-in. fillet welds. Deposition rate was 6 to 10 lb of weld metal per hour.

By changing to auxiliary-gas-shielded flux-cored arc welding, deposition rate was

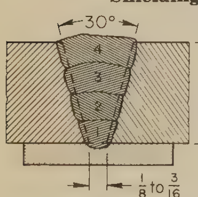
Table 3. Typical Conditions for Flat-Position Flux-Cored Arc Welding of Square Grooves and 60° Single-V Grooves in Low-Carbon Steel, Using Backing and Auxiliary Gas Shielding (CO_2 at 35 Cfh)



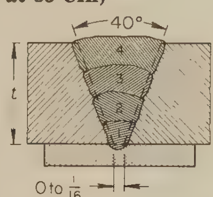
Steel thickness (*t*), in.	Number of passes	Electrode diameter, in.	Current (dcrp), amp	Voltage, v	Travel speed, ipm
Square-Groove Weld					
⅛(a) ..	1	3/32	325	24 to 26	56
3/16(b) .	1	3/32	350	24 to 26	48
60° Single-V-Groove Weld					
¼	1	3/32	375	25 to 27	41
⅜	1	⅛	500	25 to 27	24
½	2	⅛	550	27 to 30	18
⅝	2	⅛	550	27 to 30	18
¾	3	⅛	550	27 to 30	18
⅞	4	⅛	550	27 to 30	11
1	6	⅛	550	27 to 30	11

(a) Root opening (*w*), 1/32 in. (b) Root opening (*w*), 1/16 in.

Table 4. Typical Conditions for Flat-Position Flux-Cored Arc Welding of 30° and 40° Single-V Grooves in Low-Carbon Steel, Using Backing and Auxiliary Gas Shielding (CO_2 at 35 Cfh)



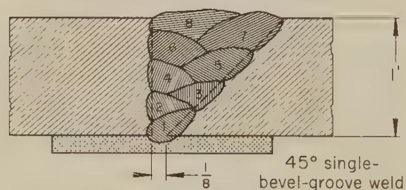
30° single-V-groove weld



40° single-V-groove weld

Steel thickness (*t*), in.	Pass number	Electrode diameter, in.	Current (dcrp), amp	Voltage, v	Travel speed, ipm
30° Single-V-Groove Weld					
⅝	1	⅛	575	31	14
	2	⅛	600	32.5	16
¾	1	⅛	575	32.5	19
	2	⅛	600	32.5	18
	3	⅛	600	32.5	15
1	1	⅛	575	31.5	21
	2	⅛	575	32	11
	3	⅛	575	32	15
	4	⅛	575	32	12
40° Single-V-Groove Weld					
⅝	1	⅛	575	32	16
	2	⅛	600	32	13
¾	1	⅛	575	32	23
	2	⅛	575	32	18
	3	⅛	600	32	15
1	1	⅛	575	31	15
	2	⅛	575	31	13
	3	⅛	575	31	15
	4	⅛	600	32	12

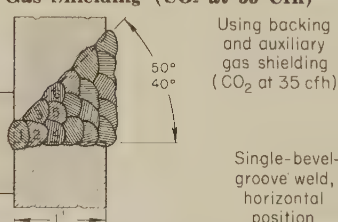
Table 5. Typical Conditions for Flat-Position Flux-Cored Arc Welding of a 45° Single-Bevel Groove in 1-In.-Thick Low-Carbon Steel, Using Backing and Auxiliary Gas Shielding (CO_2 at 35 Cfh)



45° single-bevel-groove weld

Pass number	Electrode diameter, in.	Current (dcrp), amp	Voltage, v	Travel speed, ipm
1	⅛	600	32	17
2	⅛	600	32	24
3	⅛	600	32	18
4	⅛	600	32	15
5	⅛	600	32	16
6	⅛	600	32	21
7	⅛	600	32	21
8	⅛	600	32	18

Table 6. Typical Conditions for Horizontal-Position Flux-Cored Arc Welding of a Single-Bevel Groove in 1-In.-Thick Low-Carbon Steel, Using Backing and Auxiliary Gas Shielding (CO_2 at 35 Cfh)

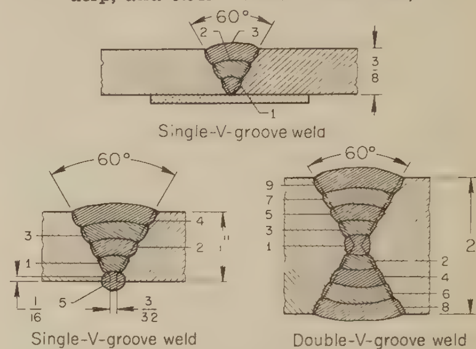


Using backing and auxiliary gas shielding (CO_2 at 35 cfh)

Single-bevel-groove weld, horizontal position

Pass number	Electrode diameter, in.	Current (dcrp), amp	Voltage, v	Travel speed, ipm
1	3/32	450	27	14
2	3/32	450	27	14
3 to 18	3/32	380	27	18

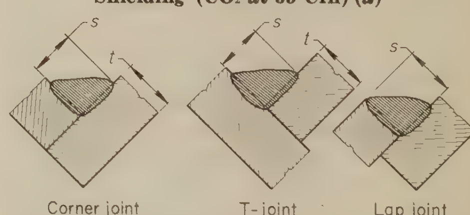
Table 7. Typical Conditions for Vertical-Position Flux-Cored Arc Welding of 60° V-Grooves in Low-Carbon Steel
(Using auxiliary shielding with CO_2 at 35 cfh, dcrp, and 0.045-in.-diam electrodes)



⅜-In. Steel(a)	2-In. Steel
Current .....180 amp	(Double-V groove; 0 to 1/16-in. root opening)
Voltage ....22 v	Current ....190 to 200 amp
Travel speed, ipm:	Voltage ....22 v
Pass 1 ....13 down	Travel speed, ipm:
Pass 2 ......7.7 up	Pass 1 ....11 down
Pass 3 ....5 up	Pass 2 ....3 up
1-In. Steel(b)	Pass 3 ......3.5 up
Current .....180 amp	Pass 4 ......2.1 up
Voltage ....22 v	Pass 5 ......2.7 up
Travel speed, ipm:	Pass 6 ....2 up
Pass 1 ....13 down	Pass 7 ......1.8 up
Pass 2 ......1.4 up	Pass 8 ......1.4 up
Pass 3 ......2.3 up	Pass 9 ......1.3 up
Pass 4 ......1.6 up	
Pass 5 ....11 down	

(a) Single-V groove with no root opening; backing used. (b) Single-V groove with 3/32-in. root opening. Before back welding (pass 5), joint is back gouged.

Table 8. Typical Conditions for Flat-Position Flux-Cored Arc Fillet Welding of Low-Carbon Steel, Using Auxiliary Gas Shielding (CO_2 at 35 Cfh) (a)



Steel thickness (*t*), in.	Electrode diameter, in.	Number of passes	Current (dcrp), amp	Voltage, v	Travel speed, ipm
⅛	3/32	1	300	24 to 26	53
3/16	3/32	1	350	24 to 26	41
	⅛	1	450	24 to 26	40
¼	3/32	1	400	24 to 26	24
	⅛	1	500	25 to 27	25
5/16	3/32	1	550	28 to 30	22
	⅛	1	460	26 to 28	20
⅜	3/32	1	575	29 to 31	20
	⅛	1	575	29 to 31	20
½	3/32	2	525	30 to 32	16
	⅛	2	525	30 to 32	16
⅝	3/32	3	475	29 to 31	12
	⅛	3	450	27 to 29	14
¾	3/32	3	500	29 to 31	13
	⅛	3	500	28 to 30	12

(a) Weld size (*s*) is usually the same as steel thickness (*t*) for the range of steel thicknesses given here.

increased to 12 to 18 lb per hour. In addition, because of the deeper penetration obtained in auxiliary-gas-shielded flux-cored arc welding, it was possible to use a ¼-in. fillet weld. The strength of the joint was equal to that of the joint made with the ⅜-in. fillet weld deposited by shielded metal-arc welding. The higher deposition rate and smaller fillet weld made flux-cored arc welding more economical. Welding details for the flux-cored arc process are given in the table accompanying Fig. 7.

Example 13 — Deeper Penetration; Increased Deposition and Arc Visibility (Fig. 8). Bulldozer blades were assembled from several low-carbon steel components that had relatively thick sections, generally ½ in. or more (see Fig. 8). Most welds were ¼ to ½-in. fillet welds. A few were groove welds.

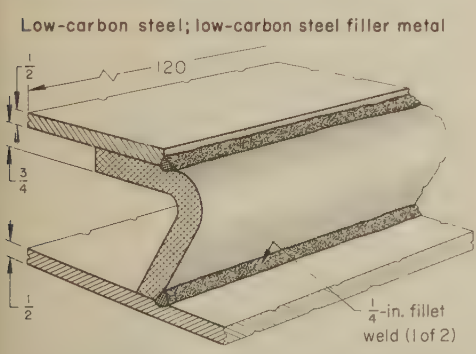
Flux-cored arc welding with auxiliary gas shielding was selected for this application in preference to shielded metal-arc welding for three reasons: (*a*) deeper joint penetration, permitting the use of smaller fillets without decreasing the strength of the joint; (*b*) higher deposition rate; and (*c*) greater visibility of the arc to the welder, resulting in a better weld.

The difference in joint penetration for the two processes is shown in Fig. 8. Details for flux-cored arc welding are given in the table accompanying Fig. 8.

Sections 3 to 15 In. Thick. Thicknesses much greater than those discussed in Examples 12 and 13 are often welded by auxiliary-gas-shielded flux-cored arc methods. The three examples that follow describe applications of this process for such sections.

Example 14. Use of Auxiliary-Gas-Shielded Flux-Cored Arc Welding and a High-Strength Electrode Wire for Welds Subjected to Heavy Loads (Fig. 9)

The shank portion of the weldment shown in Fig. 9, a component of an earthmoving machine, was subjected to heavy loads in service. Auxiliary-gas-shielded flux-cored arc welding with a high-strength electrode was selected to join the 3-in. section to the 3½-in. section, because it provided the required strength and weld quality and was faster than the shielded metal-arc welding process. Welding details, including the sequence of passes, are given in the table accompanying Fig. 9.



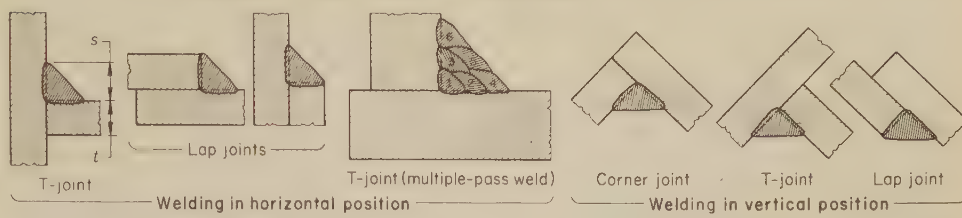
Auxiliary-Gas-Shielded Flux-Cored Arc Welding

Joint type	Lap and modified T
Weld type	¼-in. fillet
Welding position	Horizontal
Number of passes	One
Shielding gas	Carbon dioxide, at 35 cfh
Electrode	3/32-in.-diam flux-cored wire
Electrode feed	160 to 175 ipm
Current	420 to 450 amp
Voltage	29 to 31 v
Travel speed	14 to 15 ipm
Deposition rate	12 to 18 lb per hour

When shielded metal-arc welding was used, ⅜-in. fillet welds were required and deposition rate was only 6 to 10 lb per hour.

Fig. 7. Weldment of thick plates, for which process was changed from shielded metal-arc to flux-cored arc welding (Example 12)

Table 9. Typical Conditions for Flux-Cored Arc Fillet Welding in the Horizontal and Vertical Positions, Using Auxiliary Gas Shielding (CO_2 at 35 Cfh) (a)



Steel thickness (*t*), in.	Electrode diameter, in.	Number of passes	Current (dcrp), amp	Voltage, v	Travel speed, ipm
Horizontal Position					
1/8	3/32	1	350	24 to 26	60
3/16	3/32	1	400	24 to 26	41
	1/8	1	425	24 to 26	32
1/4	3/32	1	400	24 to 26	24
	1/8	1	450	25 to 27	25
5/16	3/32	1	440	25 to 27	20
	1/8	1	460	26 to 28	20
3/8	3/32	1	475	26 to 28	15
	1/8	1	500	28 to 30	14
Horizontal Position (continued)					
1/2	3/32	3	400	24 to 26	20
	1/8	3	450	25 to 27	18
5/8	3/32	3	450	26 to 28	14
	1/8	3	450	27 to 29	14
3/4	3/32	6	470	28 to 30	20
	1/8	6	470	28 to 30	20
Vertical Position					
3/8	0.045	1	180	21	3 to 4

(a) Weld size (*s*) usually equals steel thickness (*t*) for the range of thicknesses given here.

Table 10. Typical Conditions for Multiple-Position Flux-Cored Arc Welding of Grooves and Fillets, Using Various Sizes of Electrodes (a)

Electrode diameter, in.	Amperage (dcrp) and voltage (b): Flat — Amperes	Flat — Volts	Horizontal — Amperes	Horizontal — Volts	Vertical — Amperes	Vertical — Volts
0.045	150 to 225	22 to 27	150 to 225	22 to 26	125 to 220	22 to 25
1/16	175 to 300	24 to 29	175 to 275	25 to 28	150 to 200	24 to 27
5/64	200 to 400	25 to 30	200 to 375	26 to 30	175 to 225	25 to 29
3/32	300 to 500	25 to 32	300 to 450	25 to 30	...	...
7/64	400 to 525	26 to 33	...	...	...	...
1/8	450 to 650	28 to 34	...	...	...	...

(a) Flow rate of shielding gas is 30 to 45 cu ft per hour, depending on electrode size. (b) Current ranges can be expanded. Higher amperage can be used with automatic travel. Voltage will increase when longer electrical stickout is used.

Example 15. Welding 4-In.-Thick Plates for I-Beam Flange Sections (Fig. 10)

The plates shown in Fig. 10 were successfully butt welded by the flux-cored arc process with auxiliary gas shielding, using a double-V type of groove. Runoff tabs attached to both ends of the joint, after fit-up but prior to welding, provided a means for starting and stopping the weld. After welding, the runoff tabs were removed and the edges of the plates were ground smooth.

Welding was started on the side with the 60° groove (side A in Fig. 10) and was continued until that groove was about one-quarter full. The plates were then turned over and the groove area was back gouged until sound weld metal was reached. Welding was then continued on the side with the 80° groove until this groove was about half full. The plates were turned again, and welding was completed on the 60°-groove side. The plates were turned once more to the 80°-groove side, and welding was completed. Turning the plates during welding minimized distortion.

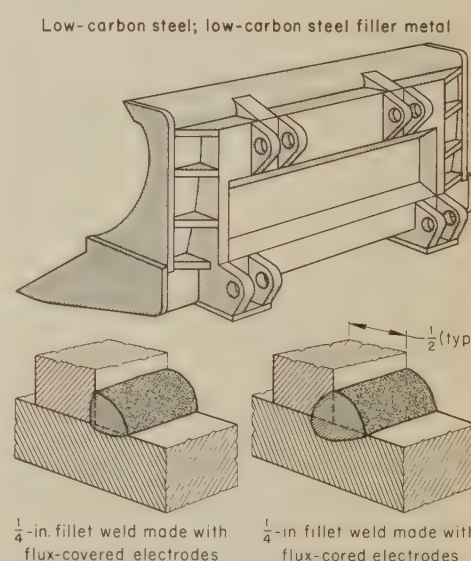
Weldments were essentially free of defects, as determined by radiographic examination and testing of side-bend specimens. Tests of transverse tensile specimens showed that the tensile strength of the welds in the stress-relieved condition ranged from 75,000 to 80,000 psi.

Welding details are given in the table accompanying Fig. 10.

Example 16. Welding of 24-by-15-In. Cross Sections (Fig. 11)

The ring shown in Fig. 11 was welded, joining two semicircular sections that had been gas cut from 24-in.-thick plate (ASTM A515, grade 70). The finished ring had a 96-in. OD and a 66-in. ID. The two welds were 15 in. thick by 24 in. long.

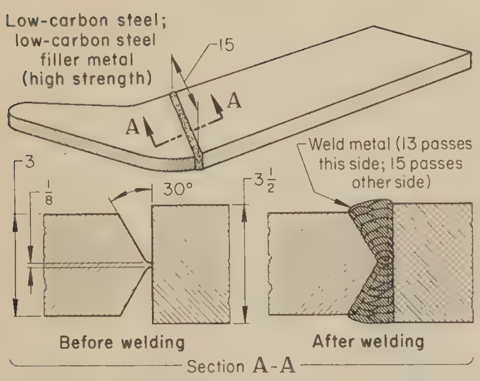
Semiautomatic flux-cored arc welding with auxiliary gas shielding was used. Welding operations are described in the table that accompanies Fig. 11. Joint pene-



Auxiliary-Gas-Shielded Flux-Cored Arc Welding

Joint type	Corner
Weld type	Fillet; some groove
Weld size	¼ to ½ in.
Welding position	Flat; horizontal
Number of passes for fillet welds:	
For ¼ and 5/16-in., flat position	One
For ⅜-in., horizontal position	Two
For 7/16 and ½-in., flat position	One
For 7/16 and ½-in., horizontal position	Three
Shielding gas	Carbon dioxide, at 35 cfh
Electrode	3/32-in.-diam flux-cored wire
Current	450 amp
Voltage	30 to 32 v
Electrode feed	206 ipm

Fig. 8. Bulldozer blade and comparison of joint penetration (and actual throat depth) of fillet welds made by shielded metal-arc welding and by auxiliary-gas-shielded flux-cored arc welding (Example 13)



Auxiliary-Gas-Shielded Flux-Cored Arc Welding

Joint type	Butt
Weld type	Double-J groove
Welding position	Flat
Shielding gas	Carbon dioxide, at 35 cfh
Electrode	3/32-in.-diam high-strength flux-cored wire
Current	450 amp, dcrp
Voltage	30 to 32 v
Electrode feed	206 ipm

Sequence of Passes

First side. Make four passes without weaving. Turn to second side.
Second side. Back gouge to obtain complete joint penetration and weld four passes as on the first side.
Alternate sides. Make two passes per side until 13 passes have been made on the first side and 15 passes on the second side. Weld from center to end; deslag after each pass; use weaving technique. Use copper dams for the last three passes on each side.

Fig. 9. Thick-section earthmover part that was flux-cored arc welded (Example 14)

tration was 100%, and distortion was held to within ½ in. of flatness. Electrode deposition efficiency was 92%.

The ring could have been welded by the submerged-arc process, but several factors favored the use of flux-cored arc welding. In the first place, a larger bevel (60° included angle) would have been needed for submerged-arc welding, which would have required twice the amount of weld metal. Secondly, slag entrapment at the bottom of the groove was less likely with flux-cored arc welding. Finally, no runoff tabs were required for flux-cored arc welding, whereas they would have been required for submerged-arc welding. In flux-cored arc welding, the welder can see and thus control the weld puddle, but in submerged-arc welding, the puddle is larger and invisible, therefore requiring runoff tabs.

Pipe Welding

When pipe sections can be rotated during welding, the operation is greatly simplified, because all of the welding can be done in the most favorable position, but when elbows or other irregular sections are involved, welding must be done with the workpieces in a fixed position unless special manipulating fixtures are provided.

Fixed-Position Welding. Although the larger sizes of flux-cored electrode wires are not suitable for welding pipe in the fixed position, development of the smaller (0.045-in.-diam) flux-cored electrode wire for welding with auxiliary gas shielding enables this to be done on low-carbon and low-alloy steel pipe sections to a quality standard that satisfies requirements of the ASME Boiler and Pressure Vessel Code.

Joint designs for welding with small-diameter flux-cored electrodes are the same as those used for shielded metal-arc welding. Joint design and pass sequence for fixed-position welding of pipe having a wall thickness of ½ in. are shown in Fig. 12. Typical welding conditions are given in the table that accompanies Fig. 12.

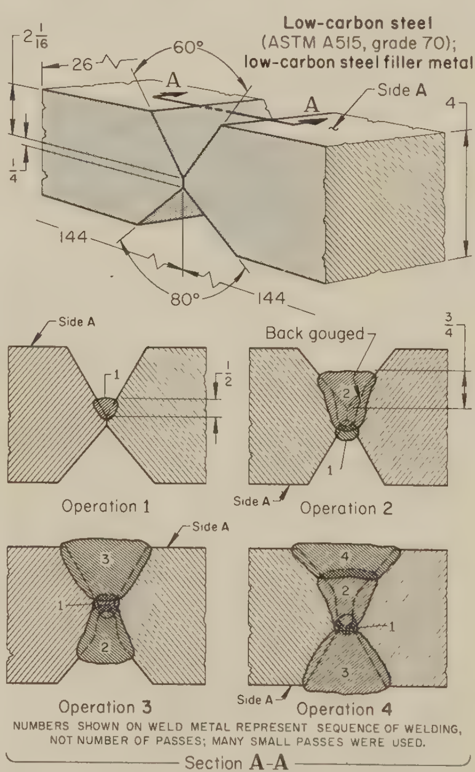
Rotation of the workpieces is greatly preferred for pipe welding and is done whenever possible. In the example that follows, thick-wall pipe and tube were rotated during welding.

Example 17. Butt Welding of Large-Diameter Thick-Wall Pipe and Tube (Fig. 13)

Steel pipe and tube, ranging in outside diameter from 8 to 36 in. and in wall thickness from ½ to 3 in., were butt welded in the horizontal-rolled position. The groove design used is shown in Fig. 13.

The root pass was made by gas metal-arc welding, using a 0.035-in.-diam solid electrode and argon – carbon dioxide shielding. Pipe was preheated to 70 F, 125 F or 200 F, depending on wall thickness (see the table accompanying Fig. 13). After preheating, maximum root opening was 3/32 in. The root pass was made with a hand-held electrode holder positioned 45° above the horizontal centerline as the pipe rotated away from the welder.

For subsequent passes (3 to 17, depending on wall thickness), flux-cored arc welding was used, with a 7/64-in.-diam flux-cored electrode wire and carbon dioxide shielding. To control the weld puddle during these passes (because a large-diameter electrode wire was employed), the electrode holder was held ½ to ¾ in. below the vertical centerline, with the pipe rotating away from the welder. Maximum width of weave was 1¼ in.

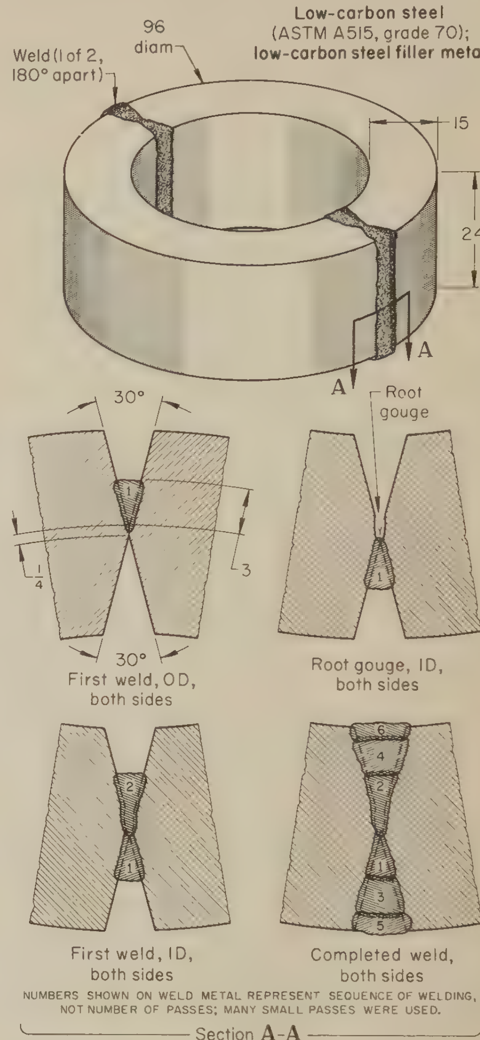


Auxiliary-Gas-Shielded Flux-Cored Arc Welding

Joint type	Butt
Weld type	Double-V groove
Welding position	Flat
Shielding gas	Carbon dioxide
Electrode	3/32-in.-diam flux-cored wire
Power supply	600-amp motor-generator, drooping output
Deposition rate	7.1 lb per hour

Fig. 10. Joint and welding sequence used for joining plates 4 in. thick by 26 in. wide by flux-cored arc welding with auxiliary gas shielding (Example 15)

When the groove width exceeded 1¼ in., the split-weave technique was used. For the first few passes that followed the root pass, the voltage and amperage were near the low end of the "remaining passes" ranges in the



Auxiliary-Gas-Shielded Flux-Cored Arc Welding

Joint type	Butt
Weld type	Double-V groove
Welding position	Flat
Shielding gas	Carbon dioxide, at 35 cfh
Electrode	7/64-in.-diam flux-cored wire(a)
Electrode holder	Air cooled, hand held
Power supply	500-amp rectifier(b)
Current	475 amp, dcrp
Voltage	30 v
Deposition rate	11 lb per hour

Welding Sequence

1 The two semicircular sections were mounted on a standard positioner so that the ring stood upright, permitting one groove on the outside to be at the top in the flat position.
2 The groove at the top was filled by multiple passes with weld metal to a depth of 3 in.
3 The ring was rotated 180°.
4 The groove at the top was filled by multiple passes with weld metal to a depth of 3 in.
5 With the ring in the same position, the groove on the inside of the first weld (now at the bottom) was root gouged with a carbon arc to obtain sound metal, and filled by multiple passes to a depth of 3 in.
6 The ring was rotated 180°.
7 The groove on the inside of the second weld (now at the bottom) was root gouged and filled by multiple passes with weld metal to a depth of 3 in.
8 The above sequence was continued (without root gouging) until all grooves were filled.

(a) 0.09 C, 1.00 Mn, 0.45 Si. (b) Constant voltage.

Fig. 11. Large ring made by joining two 15-in.-thick semicircular sections by flux-cored arc welding (Example 16)

table with Fig. 13. As the depth of weld buildup increased, lessening the possibility of melt-through, voltage and amperage were increased to the high end of these ranges. Travel speed varied with pipe diameter; it was controlled to ensure that slag did not run ahead of the arc. Slag was removed between passes. Deposition rate for flux-cored arc welding ranged from 15 to 25 lb per hour.

Further details of procedures and equipment are given in the table that accompanies Fig. 13.

Typical mechanical properties of the weld metal were 76,000 psi tensile strength, 67,000 psi yield strength, 32% elongation, and 68% reduction of area. Charpy V-notch impact values of the weld metal at selected temperatures were as follows: 92 ft-lb at 75 F, 75 ft-lb at 0 F, 48 ft-lb at −40 F, and 30 ft-lb at −75 F.

The joint and procedures were qualified by tests made according to Section IX of the ASME Boiler and Pressure Vessel Code; ANSI B31.3, American National Standard Code for Pressure Piping; and U.S. Navy S-9-1, General Specification for Ships.

Arc Spot Welding

In arc spot welding, a weld is made in a lap joint through one piece of metal into the other piece. There is no travel of electrode holder or workpiece. For thin sheets, the weld is a melt-through weld, made without preparing a hole in the top sheet.

Thickness and Position Limitations. Flux-cored arc spot welding is used to make lap joints in low-carbon steel 1/16 to 1/4 in. thick. Sheet or plate of the same or of different thicknesses can be welded together. If stock of different thicknesses is being welded, the weld should be made from the side of the thinner member. Arc spot welding is best done in the flat position, although thin sheet can be welded in other positions.

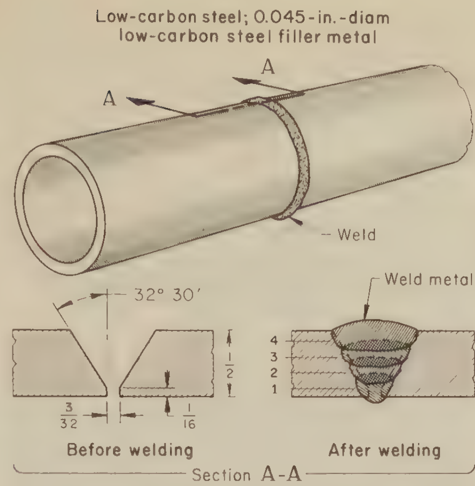
Typical Procedures and Conditions. In flux-cored arc spot welding, an air-cooled electrode holder equipped with a special nozzle is held against the top member of a lap joint. The arc, which is maintained by the continuously fed electrode, melts through the top sheet and into the bottom sheet, and fuses the two sheets together. The electrode continues to feed for a preset arc time and produces a slightly convex spot on the upper surface of the top sheet.

Most flux-cored arc spot welding is done with carbon dioxide shielding, because shielding provides deeper penetration. However, the self-shielding method can be used for arc spot welding of thin sheet (up to 1/8 in. thick).

Typical welding conditions for flux-cored arc spot welding of steel from 1/16 to 1/4 in. thick are given in Table 11.

Weld Characteristics. The strength of arc spot welds produced by flux-cored arc welding is about the same as that produced by resistance welding in steel of the same thickness. Typical values of shear strength of arc spot welds are given in Table 11.

Arc spot welding with a flux-cored electrode offers several advantages over arc spot welding with a solid electrode. Generally, the weld nugget is larger at the interface when welding through metal of the same thickness, which results in higher strength per spot. Also, with a flux-cored electrode, there is a slag cover on the surface of the weld, which results in a smoother surface and, for some applications, eliminates



Pass	Current (dcrp), amp	Voltage, v	Gas (CO_2) flow, cfm	Travel direction
1	100	20	25	Down
2, 3, 4	120	20	25	Up

Interpass temperature 300 F; pipe axis horizontal

Fig. 12. Joint design and pass sequence for fixed-position welding of 1/2-in.-wall pipe with a 0.045-in.-diam electrode wire

the necessity for a finishing operation.

A flux-cored electrode has been found to be better than a solid electrode for spot welding galvanized steel; it provides smoother surfaces and deeper penetration. Also, weld spatter from flux-cored electrodes does not adhere to galvanized surfaces. For spot welding of galvanized steel, the current is reduced slightly and the arc time is increased, compared with spot welding of uncoated sheet of the same thickness.

Automatic Welding

Flux-cored arc welding can be done automatically, using essentially the same techniques as for gas metal-arc welding. Electrode holders used for automatic gas metal-arc welding can be used also for automatic flux-cored arc welding (see the section on Electrode Holders, page 25). Power supply, wire feeders, and other basic equipment for automatic welding are described on pages 25 and 26.

The quantity of similar weldments required determines whether or not automatic welding is feasible and the degree of automation that is appropriate. For some applications, quality requirements are so high that they can be met economically only by automatic welding.

Automatic welding is most advantageously applied to long in-line welds such as long seam welds and girth welds on large pipes. Tooling cost for an application of this type is generally moderate, but increases as weld complexity increases.

In most applications, tooling can be simplified by moving the components to be welded while the electrode holder remains stationary. If the workpiece is large or of complex shape, moving it past the electrode holder may not be practical, and the more costly alternative of moving the electrode holder will have to be adopted.

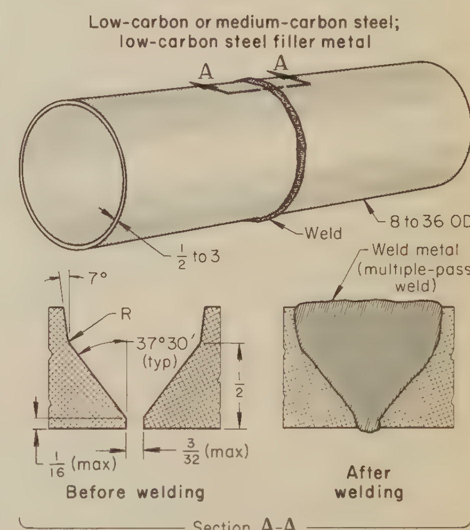
Circumferential welding is usually easy to automate, because round workpieces of all sizes can almost always be held and rotated without difficulty. In practice, the electrode holder remains stationary and makes the weld as the workpiece slowly rotates.

The three examples that follow describe applications in which automatic welding was advantageous.

Table 11. Typical Conditions for Flux-Cored Arc Spot Welding and Shear Strength Per Spot

Steel thickness, in.	Current (dcrp), amp	Voltage, v	Arc time, sec	Shear strength per spot, lb
With Carbon Dioxide Shielding(a)				
1/16	400	30	0.6	2,550
1/8	500	34	0.8	3,400
3/16	650	38	1.6	7,050
1/4	750	40	2.2	10,300
Self-Shielding(b)				
1/16	500	29	0.5	2,250
1/8	500	29	1.5	2,450

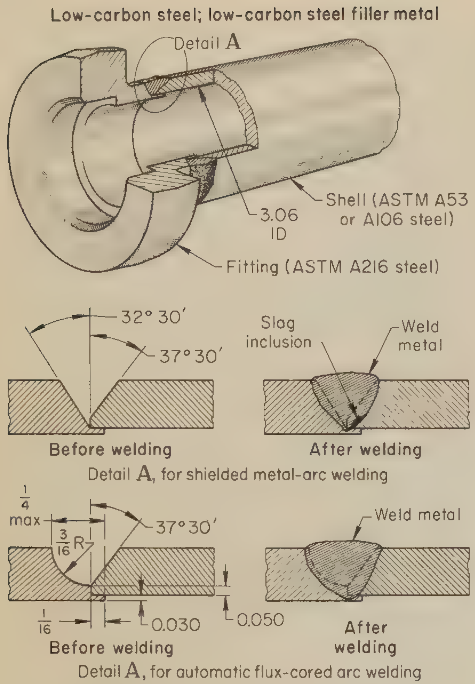
(a) 3/32-in.-diam E70T-2 electrode; electrical stickout, 7/8 in.; flow rate of shielding gas, 35 cu ft per hour. (b) 3/32-in.-diam E70T-4 electrode; electrical stickout, 1½ in.



Joint type ....Circumferential butt
Weld type ....Modified U-groove
Process ....Gas metal-arc and flux-cored arc(a)
Welding position ....Horizontal rolled
Fixture ....Variable-speed turning rolls
Preheating:
  ½ to 1½-in. wall thickness ....70 F
  1½ to 2¼-in. wall thickness ....125 F
  2¼ to 3-in. wall thickness ....200 F
Shielding gas:
  Root pass ..75% A – 25% CO_2, at 15 to 20 cfh
  Remaining passes ....CO_2, at 40 to 45 cfh
Electrode:
  Root pass ....Solid wire(b)
  Remaining passes ....Flux-cored wire(c)
Power supply ....500-amp constant-voltage three-phase rectifier, with slope control
Current and voltage:
  Root pass ....90 to 110 amp, 17 to 19 v
  Remaining passes ....300 to 475 amp, 24 to 28 v
Wire feeder ....Constant-feed, either two standard units or a special unit featuring dual-drive mechanism

(a) Root pass was made by gas metal-arc welding and remaining passes by flux-cored arc welding with auxiliary gas shielding. (b) Composition, 0.06 C max, 1.20 Mn, 0.50 Si, 0.05 to 0.15 Al, 0.02 to 0.12 Zr, 0.05 to 0.15 Ti. (c) Composition, 0.09 C, 1.00 Mn, 0.45 Si.

Fig. 13. Circumferential butt weld in pipe or tubing 8 to 36 in. in outside diameter and ½ to 3 in. in wall thickness, and joint design. Horizontal-rolled position was used in making the weld. (Example 17)



Automatic Flux-Cored Arc Welding

Joint type	Modified lap and butt (see figure)
Weld type	Groove (see figure)
Welding position	Horizontal rolled
Preheat	None
Shielding gas	Carbon dioxide, at 30 cfh
Electrode	5/64-in.-diam E70T-5
Electrode holder	Air cooled, mechanically held
Power supply	500-amp constant-voltage three-phase rectifier
Current	430 amp, dcrp
Voltage	28 v
Wire feeder	Constant feed
Welding time:	
Root pass	16 sec
Cover pass	22 sec

Fig. 14. Heat-exchanger shell and fitting, and joint designs for shielded metal-arc and automatic flux-cored arc welding (Example 18)

Example 18. Change From Shielded Metal-Arc Welding to Automatic Flux-Cored Arc Welding of Heat-Exchanger Components (Fig. 14)

A shell and a fitting for a heat exchanger were originally joined by shielded metal-arc welding. Because of the relatively small diameter of the workpiece (3-in. schedule 40 pipe) and the requirement for 100% joint penetration, a 3/32-in.-diam electrode wire was the maximum size that could be used. Welding was slow, because of the small size of the electrode wire and the need for removal of slag between passes. An average of 13 min was required to complete the peripheral V-groove weld, using the joint design shown in Fig. 14. Even under these conditions, and with the services of a highly skilled welder, rejections were excessive because of slag inclusions and inadequate joint penetration.

In contrast, after procedures were established, fully automatic welding, using a 5/64-in.-diam flux-cored electrode wire (E70T-5) completed a root pass and a cover pass in 38 sec. For automatic flux-cored arc welding, the joint was redesigned as shown in Fig. 14, although the 37½° bevel angle was retained on the shell. This change in joint design prevented slag inclusions and lack of penetration. Because use of electrode wire E70T-5 results in a very thin friable slag layer, it was possible to make the two-pass weld without removing slag between passes. Even with a relatively unskilled operator, acceptable parts were produced more consistently.

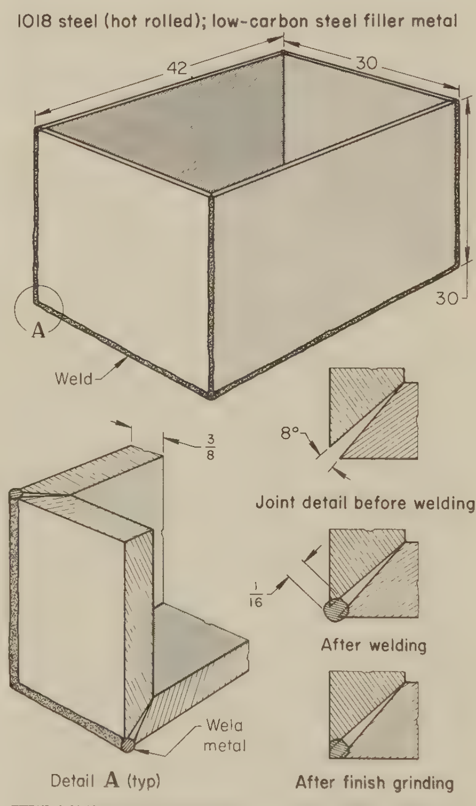
Conditions for automatic flux-cored arc welding are given in the table that accompanies Fig. 14. A mechanically held, retractable, air-cooled electrode holder was used. Other special tooling included an air-operated internal chucking device to pull the shell into intimate contact with the fitting, equipment for automatic loading and unloading of shells, and a mechanism for variable-speed rotation.

It was required that the welding procedure be qualified by tests performed in accordance with Section IX of the ASME Boiler and Pressure Vessel Code.

Example 19. Automatic Flux-Cored Arc Welding for Fabricating Security Boxes (Fig. 15)

An open-top box (Fig. 15), 42 in. long by 30 in. wide by 30 in. deep, made of 3/8-in.-thick low-carbon steel, was used as the inner receptacle of a government security file. A partial-penetration seal weld, deposited from the outside, was adequate for joining the five plates of which the box was made. Automatic flux-cored arc welding with carbon dioxide shielding was selected because a high production rate was desired and because the uniform joint conditions were well suited to automatic welding.

The special equipment needed for automatic welding consisted of an electrode holder mounted on a motor-driven carriage, a 4-ft-diam indexing turntable, and a toggle-clamp fixture for assembling the box and maintaining joint alignment during welding. Electrode-holder travel, gas flow, water flow, welding current, and wire feed were initiated by a starting switch and terminated by a limit switch.



Joint type	Corner
Weld type	8° groove
Edge preparation	Bevel to 41°
Welding position	Horizontal
Fixture	Toggle clamp
Preheat and postheat	None
Number of passes	One
Shielding gas	Carbon dioxide, at 30 cfh
Electrode	3/32-in.-diam flux-cored wire
Electrode-feed rate	130 ipm
Power supply	500-amp constant-voltage rectifier
Current	300 amp, dcrp
Voltage	24 v
Wire feeder	Constant feed
Production time	21 min per box

Fig. 15. Inner box for security file that was produced by automatic flux-cored arc welding, and joint details (Example 19)

Joint edges were beveled to 41° and then the plate sections were assembled on the turntable in the toggle-clamp fixture, with the 30-by-30-in. sides in the horizontal position. The turntable was indexed under the electrode holder for a horizontal single-pass weld on one corner. After this weld was completed, the turntable was indexed for each of the succeeding welds, until one side was completed (three joints). The box was then turned over manually, and the process was repeated for the three joints on the opposite side. The two 42-in. joints were then welded in a similar manner. The completed welds were ground to size as shown in Fig. 15. Conditions for welding are given in the table with Fig. 15.

Total welding time per box was 21 min: 2.5 min for each of the six short welds and 3 min for each of the two long welds.

Requirements for the welded joints were that they be completely sealed against passage of light and moisture, and that they have high strength and a joint penetration of approximately 0.060 in. Sample welds that were produced along with the boxes were examined microscopically for penetration, and 2% of the weldments were tested for tensile strength. Rejection rate averaged 0.5%.

Example 20. Welding Long Channel Sections by Automatic Flux-Cored Arc Welding (Fig. 16)

The fully automatic equipment for flux-cored arc welding shown in Fig. 16 was developed to butt weld two structural channels into a box section for a hitch for a gang plow. Originally, the box sections had been produced by shielded metal-arc welding. Cost of welding was reduced about 40% by using the auxiliary-gas-shielded flux-cored arc method. A principal factor in the decrease in cost was reduction of labor from two welders to one operator.

The channels were cut to length and all holes were punched in a progressive die so as to make a pair of channels, one a right-hand section and the other a left-hand section. Channel length was from 30 in. to 13½ ft for different designs.

The operator slid a pair of channels onto a roller conveyor, ahead of the entry end of the welding machine, and aligned the channels to form the box. The channels were then pushed into the welding machine on rollers, which became the bottom supporting surface for the workpiece during welding. A pin was inserted through holes in the frame of the machine and through matching holes in each end of the pair of channels, to hold hole alignment. Next, air cylinders were actuated by a foot switch to clamp the workpiece. The electrode holder was brought into line, the drive was locked, and the start button was pushed to begin welding on the first side. The locating pins were removed as the welding head progressed along the seam.

On completing the first seam, the welding head was returned to the starting position, the air clamps were released, and by means of an air-operated linkage, the rollers supporting the channels were raised above the machine frame so that the workpiece could be turned over to weld the second side. The rollers were then lowered, the workpiece was reclamped, and the second side was welded. On completion of the second weld, the air clamps were released, the weldment was struck six or more blows with a hammer to free flux deposits, and the workpiece was pushed out onto a conveyor table.

Because the equipment operated automatically, the operator was free to prepare the next pair of channels while the pair in the machine was being welded. While the second pair was being welded, the completed workpiece was removed from the exit conveyor table to a skid, by means of a bridge crane.

The welding machine was extremely versatile. Various sizes of channels were welded, ranging from 4 by 1¾ to 6 by 3 in.

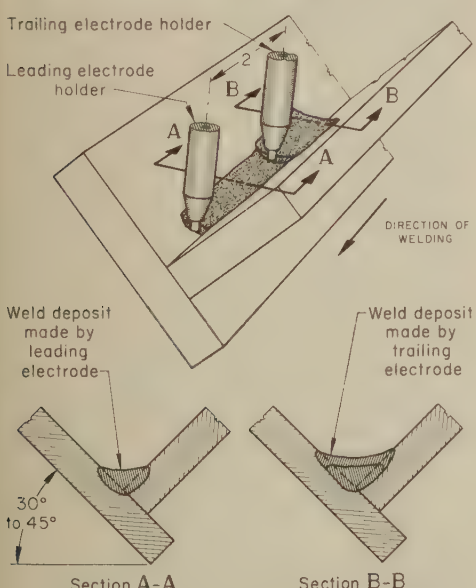
and in length from 30 in. to 13½ ft. V-notches were added to the clamping jaws to make possible welding of straight-line corner joints joining pairs of angles into box sections, and the gas nozzle on the electrode holder was pointed 8° to 10° in the travel direction, to expel dirt, rust and oil from the joint area and to spread the weld deposit. Joint penetration was found to be 90 to 95%.

In the original method (shielded metal-arc welding), a 5/32-in.-diam E7018 electrode was operated at 275 amp dcrp, 30 to 31 volts, at a travel speed of 10 to 12 in. per minute.

Submerged-arc welding was considered as an alternative process for joining the structural channels, but the channels did not match up evenly enough for this type of welding. In addition, it was estimated that the removal of unfused flux would require too much time, and that the consumption of flux would be excessive.

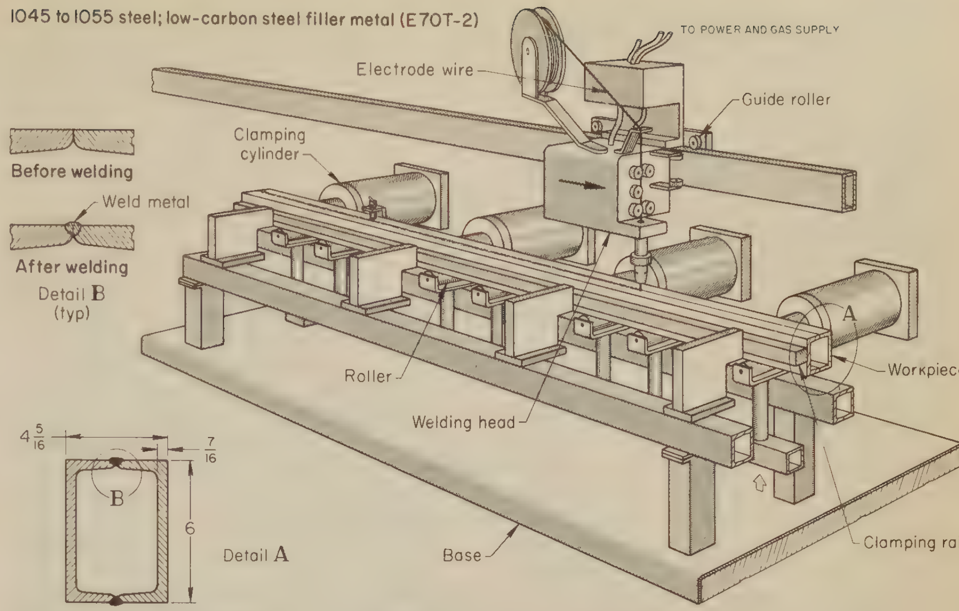
Details for automatic flux-cored arc welding of the channel sections are given in the table that accompanies Fig. 16.

Twin-Electrode (Twin-Wire) Welding. When automatic welding equipment is used, two electrode holders can be mounted on a single carriage for twin-electrode flux-cored arc welding (see Fig. 17). For example, the twin-electrode technique was used for depositing horizontal fillet welds ¼ to ⅜ in. in size and flat fillet welds up to ¾ in. in size. Both of the electrode wires were ⅛ in. in diameter, and they were in line along the weld joint, with one electrode trailing about 2 in. behind the other. Thus, there were two arcs and two separate weld puddles. The two weld puddles were smaller and were more easily controlled than the single, larger puddle that would have resulted if a weld of the same size had been deposited from a single electrode in one pass. Electrode positions used for the twin-electrode technique are shown in Fig. 17, and typical welding conditions for depositing ½ and ⅞-in. fillet welds are given in the table that accompanies Fig. 17.



Fillet size, in.	Electrode diam, in.	Total current (dcrp), amp	Voltage, v	Travel speed, ipm
½	⅛	1300	35 to 36	34
⅞	⅛	1300	35 to 36	13

Fig. 17. Position of electrodes, and weld deposits made, for automatic twin-electrode welding in the flat position



Number of passes	One	Electrode consumption	9 lb per hour
Preheat and postheat	None	Power supply	600-amp constant-voltage motor-generator
Shielding gas	Carbon dioxide, at 45 cfh	Current	290 to 300 amp, dcrp
Electrode	3/32-in.-diam E70T-2	Voltage	29 to 30 v
Electrode holder	Mechanically held, CO_2 cooled	Wire feeder	Constant feed
Electrode-feed rate	95 ipm	Travel speed	62 to 65 ipm
Electrical stickout	1¼ in. max		

Fig. 16. Machine for automatic flux-cored arc welding of long channels into box sections. Joint design and location for welds on the box section are shown at the left. (Example 20)

Cost

Flux-cored arc welding competes successfully with other arc methods used for welding steel, and for many applications, it is less costly than the other arc methods.

Costs for specific welding applications are given in the five examples that follow. The first three compare the cost of flux-cored arc welding with the cost of another arc welding process.

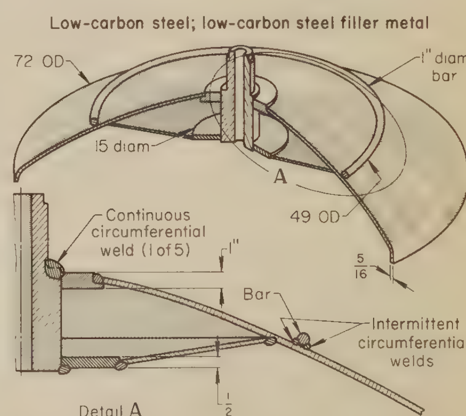
Example 21. Cost of Welding Trunnions on Tank Heads — Flux-Cored Arc Welding vs Submerged-Arc Welding (Fig. 18)

Substantial quantities of tank heads with reinforced trunnions were required for processing vessels that would be rotated. A typical 6-ft-diam head made of 5/16-in.-thick low-carbon steel, with the trunnion assembly welded in place, is shown in Fig. 18. Originally, the parts were assembled on a table, tack welded in place, and welded with the shielded metal-arc process. Because of the quantity involved, the possibility of using an automatic process was examined. A fixture in the shape of a circular cradle was constructed to hold the head and the trunnion in proper alignment, the cradle was mounted on a welding positioner, and, as the equipment was available, the welds were made by the submerged-arc process. This procedure reduced production time and resulted in welds that were more uniform and had a better appearance.

Further study showed that considerable time was being spent in setting up the submerged-arc equipment for each of the seven circumferential welds. For the shorter welds especially, setup time was high compared with arc time. It was therefore decided to try automatic flux-cored arc welding with auxiliary gas shielding.

The only new equipment needed was a wire feeder, an electrode holder, hoses and shielding gas. The electrode holder was clamped to a stationary support as before, and the same cradle fixture was used.

As shown in the comparative cost data accompanying Fig. 18, production time per part was cut in half by flux-cored arc welding and welding cost was reduced by approximately one-third.



Item	Submerged-arc welding	Flux-cored arc welding
Time and Cost per Assembly(a)		
Production time, hr	4	2
Labor & overhead ($10/hr)	$40.00	$20.00
Electrodes (about 22½ lb)	4.50	10.10
Flux (about 10 lb)	1.30	....
Total cost per assembly	$45.80	$30.10(b)

(a) Estimate; accurate within 10%. (b) Cost of carbon dioxide shielding gas was negligible.

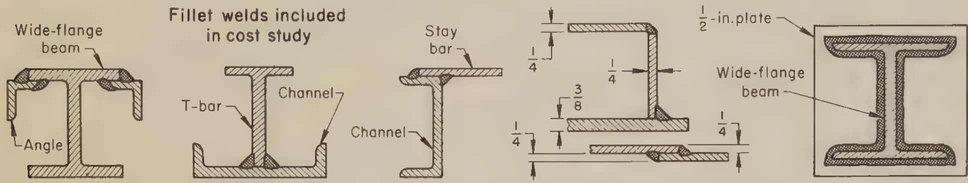
Fig. 18. Head-and-trunnion assembly for which automatic flux-cored arc welding was less costly than automatic submerged-arc welding (Example 21)

Example 22. Cost of Making Fillet Welds — Flux-Cored Arc Welding vs Shielded Metal-Arc Welding (Table 12)

To compare the cost of making single-pass fillet welds by shielded metal-arc welding and by flux-cored arc welding without externally applied gas shielding, a 60-day study was conducted. The cost elements were: (a) labor and overhead for depositing 100 lb of weld metal, and (b) electrode cost for depositing 100 lb of weld metal.

Table 12. Cost for Making Single-Pass Fillet Welds by Shielded Metal-Arc Welding and Flux-Cored Arc Welding Without Auxiliary Gas Shielding (Example 22) (a)

Item	Shielded metal-arc welding	Flux-cored arc welding(b)
Electrode size, in.	3/16	3/32
Welding current (dcrp), amp	275	350
Deposition rate, lb of metal deposited per arc-hr	8.1	15.5 (c)
Operator factor, arc-hr per man-hr, %	30	40
Deposition factor, lb of metal deposited per man-hr	2.43	6.2
Man-hours to deposit 100 lb of metal	41.15	16.13
Labor and overhead rate, per hr	$10.00	$10.00
Labor and overhead cost, per 100 lb of metal deposited	$411.50	$161.30
Electrode-deposition efficiency, lb of metal deposited per lb of electrode used, %	60	85
Electrode consumption, lb per 100 lb of metal deposited	167	118
Electrode cost per 100 lb	$21.00	$23.00
Electrode cost per 100 lb of metal deposited	$25.07	$27.14
Total cost per 100 lb of weld deposit	$436.57	$188.44

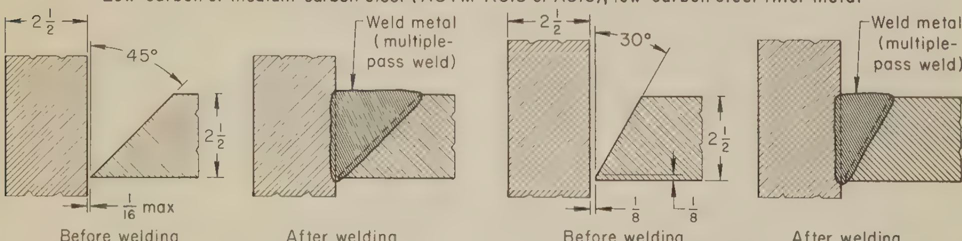


(a) Based on a 60-day study of 3/16 to 3/8-in. single-pass fillet welds of the types shown in the views above. (b) Self-shielding. (c) Using an average electrode-feed rate of 204 in. per minute.

Table 13. Conditions and Costs for Welding 2½-In.-Thick Steel Plates by the Shielded Metal-Arc Process and the Flux-Cored Arc Process With Auxiliary Gas Shielding (Example 23)

Item	Shielded metal-arc welding	Flux-cored arc welding
Welding Conditions		
Preheat	250 F	250 F
Electrode classification	E7018	E70T-1
Electrode diameter, in.	Passes 1 to 4, 1/8 Passes 5 to 7, 5/32 Rem passes, 1/4	All passes, 1/8
Electrode-feed rate	Manual	Voltage control
Welding position	Flat	Flat
Interpass temperature	250 F min	250 F min
Number of passes (average)	80	50
Current (dcrp), amp	Passes 1-4, 110 to 140 Passes 5-7, 130 to 190 Rem passes, 260 to 300	All passes, 550 to 575
Voltage	23 to 28 v	30 to 32 v
Shielding gas	....	CO_2, at 45 cfh
Power supply (both processes)	600-amp rectifier	
Cost Comparison		
Metal deposited, lb per ft	13.3	8.8
Electrode consumption:		
Lb per ft of metal deposited	22	12
Lb per lb of metal deposited	1.65	1.37
Deposition rate, lb of metal deposited per arc-hr	12	16
Operator factor, arc-hr per man-hr, %	20	33
Deposition factor, lb of metal deposited per man-hr	2.4	5.3
Production time, man-hr per lb of metal deposited	0.415	0.187
Labor and overhead rate, per hr	$10.00	$10.00
Labor and overhead cost, per lb of metal deposited	$4.15	$1.87
Electrode cost, per lb	$0.15	$0.28
Electrode cost, per lb of metal deposited	$0.248	$0.384
Shielding gas cost, per lb of metal deposited	...	$0.01
Cost Summary (for Depositing One Pound of Metal)		
Labor and overhead	$4.15	$1.87
Electrode	0.248	0.384
Shielding gas	...	0.01
Total cost per pound of metal deposited	$4.398	$2.264

Low-carbon or medium-carbon steel (ASTM A515 or A516); low-carbon steel filler metal



Original method (shielded metal-arc welding, E7018 electrode)
Improved method (flux-cored arc welding, E70T-1 electrode)

The fillet welds (shown in Table 12) ranged in size from 3/16 in. to 3/8 in. They were single-pass welds, deposited in the flat and horizontal positions. All welds could be made by both of the processes being studied. Steel thickness was ¼ to ½ in.

For shielded metal-arc welding, a 3/16-in.-diam E7024 iron powder electrode was used because it produced smooth welds at high speed, with low spatter. The flux-cored electrodes were of low-carbon steel and were 3/32 in. in diameter. A 400-amp motor-generator was used for shielded metal-arc welding; welding current was 275 amp, dcrp. A 600-amp motor-generator and wire feeder were used for flux-cored arc welding; welding current was 350 amp, dcrp.

Table 12 summarizes the results of this study. Electrode-deposition efficiency was lower for shielded metal-arc welding than for flux-cored arc welding because a greater part of the weight of the flux-covered electrodes was flux [see the comparison of flux-covered and flux-cored electrodes on page 27], spatter loss was greater, and electrode stub ends had to be discarded. The operator factor for shielded metal-arc welding was also less because of the time consumed in changing electrodes and restriking the arc. As a result, electrode consumption per 100 lb of deposited weld metal was considerably higher for shielded metal-arc welding, as were man-hours per 100 lb of deposited weld metal. Table 12 shows cost for flux-cored arc welding to be less than one-half the cost for shielded metal-arc welding.

Example 23. Cost of Welding 2½-In.-Thick Steel Plates — Flux-Cored Arc Welding vs Shielded Metal-Arc Welding (Table 13)

Press-platen assemblies, each made of more than 30 plates of 2 to 2½-in.-thick steel (ASTM A515 or A516), were originally welded by the shielded metal-arc process. After a cost and processing study, flux-cored arc welding with auxiliary gas shielding was adopted for these assemblies.

Most of the welds joining the plates were full-penetration single-bevel groove welds made at T-joints. Single-bevel, rather than double-bevel, design was used because the holding fixtures used for assembly limited access to the joint.

A typical single-bevel groove in a T-joint is shown in Table 13. For shielded metal-arc welding, a 45° single bevel with a minimum root opening was used, but for flux-cored arc welding with carbon dioxide shielding, a 30° bevel could be used, thereby reducing the volume of filler metal required by more than a third. A smaller groove could be used because of the deep-penetration characteristic of flux-cored arc welding and the use of a reasonably long electrical stickout (1½ in. with a ¾-in.-OD nozzle).

Other advantages of auxiliary-gas-shielded flux-cored arc welding were: (a) higher deposition rate, (b) higher operator factor, and (c) lower electrode cost. Power cost was not considered significant, and shielding gas cost was a relatively minor factor. Cost factors and welding conditions for both processes are given in Table 13. The three principal items affecting cost were:

1 **Deposition rate,** in pounds of weld metal deposited per arc-hour, which was determined by actual measurement of weld metal deposited for specific electrical conditions during a specific time interval (usually 10 min)

2 **Electrode consumption,** in pounds of electrode required per foot of weld deposit, which was obtained from an actual job analysis

3 **Operator factor,** the ratio of actual welding time (arc-hours) to total payroll time, determined on a daily basis and expressed as a percentage. (The relatively low operator factor in this application was still better than normal for manual and semiautomatic welding of this type. The welder did other work besides welding.)

Example 24. Cost of Fillet Welding Condenser Shells (Table 14)

Two-pass fillet welds that were from ¼ to 3/8 in. in size and less than 10 ft long

were required in fabricating shells of surface condensers. Typical ⅜-in. fillet welds made by flux-cored arc welding with auxiliary gas shielding are shown in Table 14; cost and welding data are also given.

Welding was done in the horizontal position. The welder held the torch at a lead angle of 5° to 15° pointed in the direction of the completed weld (backhand welding). For the first pass, the angle of the electrode to the work was approximately 45°, with the tip of the electrode pointed ⅛ in. outside the intersection of the joint. For the second pass, the 45° angle was used again, and the electrode tip was directed so as to deposit the second bead above the first bead.

The cost data in Table 14 were obtained from production figures and were averaged out. The average values were then converted to rates. The operator factor takes into account various duties associated with weld deposition (such as cleaning slag between passes) and operator rest time.

Example 25. Cost of Auxiliary-Gas-Shielded Flux-Cored Arc Welding To Supplement Automatic Submerged-Arc Welding for Making Pump Casing Bends (Table 15)

Pump casings that were intended to deliver large volumes of water under pressure were fabricated from hot rolled low-carbon steel plate (ASTM A285, grade C), in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code. Longitudinal and circular joints were welded by the submerged-arc process, because with this process fixturing for automatic arc travel was simple. However, on offsets, segmented elbows, and bends, the mitered girth joints were not suited to automatic travel because of the elliptical contour and the angle made with the axis of the casing. For joints of this type, flux-cored arc welding with auxiliary gas shielding was used. A typical 30° bend in a three-section, 50-in.-OD casing, with two mitered girth joints, is shown in Table 15.

Edges were prepared for the two mitered joints by gas cutting the segments from a single length of fabricated casing. Contour and bevel were cut in the same operation in the gas cutting machine. The center section was rotated 180° from its original location, and the joints were tack welded and checked for dimensional accuracy. Next, the flange at one end of the assembly was bolted to the faceplate of a rotating positioner. The preheat temperature requirement of 70 F was met by warming the workpiece with a gas torch, when necessary.

Cost and welding details are summarized in Table 15. Use of semiautomatic flux-cored arc welding permitted the welder to guide the arc visually to the contour of the joint. In addition, the deposition efficiency (weight of electrode deposited as usable metal compared to weight consumed) was 80 to 85%.

Flux-Cored Arc Welding vs Alternative Welding Processes

For applications in which two or more welding processes can produce acceptable results, the choice of process depends mainly on the equipment available, the skill of the welders, the number of similar weldments to be produced, and the cost. For some applications, shielded metal-arc, gas metal-arc, and submerged-arc welding compete with flux-cored arc welding.

Flux-Cored Arc Welding vs Shielded Metal-Arc Welding. Although flux-cored arc welding is less versatile than shielded metal-arc welding, it is usually faster, because it uses a continuously fed electrode wire. Also, the flux-cored method with auxiliary gas shielding results in deeper penetration, which often permits a smaller fillet to be used to achieve the required joint strength, thus requiring less filler metal.

Development of small-diameter flux-cored electrode wires has increased the versatility of flux-cored arc welding. Prior to this development, flux-cored arc welding was generally restricted to welding in the flat and horizontal positions. The example that follows compares flux-cored arc welding with shielded metal-arc welding for making vertical welds.

Example 26. Flux-Cored Arc Welding With Auxiliary Gas Shielding vs Shielded Metal-Arc Welding for Vertical Groove Welds (Table 16)

A study was conducted to compare flux-cored arc welding with shielded metal-arc welding for making ¼-in. vertical groove welds 12 in. long on ¼, ⅜ and ½-in.-thick steel plates. The time required to make these welds is shown in Table 16. Flux-cored arc welding proved to be three to four times faster than shielded metal-arc welding.

Joint design for the two processes is shown in Table 16. The ⅛-in. flux-covered electrode required a relatively wide root opening for the root pass, but a narrow root opening could be used for making the root pass with the 0.045-in. flux-cored electrode. The lower total time for flux-cored arc welding resulted from fewer passes (for the ⅜ and ½-in.-thick plates), less arc time, and less cleaning time.

Examples 12, 13, 22 and 23 in this article also compare flux-cored arc welding with shielded metal-arc welding. In the 18 examples that follow, flux-cored arc welding was selected because of the higher production rates resulting from smaller fillets, fewer passes, and a higher operator factor. In Examples 29, 30 and 31, flux-cored arc welding without gas shielding was used; in the other examples, carbon dioxide shielding was used.

Example 27. Flux-Cored Arc Welding With Auxiliary Gas Shielding vs Shielded Metal-Arc Welding for Production of Brake Supports (Fig. 19)

Brake supports for earthmoving equipment were built from several components that varied in thickness from ¼ to ¾ in.

Table 14. Conditions and Costs for Fillet Welding of Condenser Shells by the Flux-Cored Arc Process With Auxiliary Gas Shielding (Example 24)

Welding Conditions	
Joint type	T-joint
Weld type	Fillet
Welding position	Horizontal
Preheat	70 F
Number of passes	Two
Shielding gas	Carbon dioxide, at 45 cfh
Electrode	3/32-in.-diam E70T-1
Electrode holder	500 amp, air cooled
Electrode-feed rate	160 ipm
Electrical stickout	1 in.
Power supply	500-amp constant-voltage rectifier
Current	380 to 400 amp, dcrp
Voltage	26 to 28 v
Travel speed	14 to 16 ipm
Postheat	None
Cost Data	
Metal deposited, lb per ft	0.349
Deposition rate, lb of metal deposited per arc-hr	12.50
Operator factor, arc-hr per man-hr	33%
Deposition factor, lb of metal deposited per man-hr	4.13
Electrode-deposition efficiency, lb of metal deposited per lb of electrode used	90%
Electrode cost, per lb	$0.30
Electrode cost, per lb deposited metal	$0.33
Shielding gas cost, per lb deposited metal	$0.01
Labor and overhead rate, per hr	$10.00
Total cost, per man-hr	$11.40

Cost Summary	Cost per lb of metal deposited	Cost per foot (two beads)
Labor and overhead	$2.42	$1.69
Electrode	0.33	0.23
Shielding gas	0.01	0.01
Total	$2.76	$1.93

Low-carbon steel (ASTM A285, grade C); low-carbon steel filler metal (E70T-1)

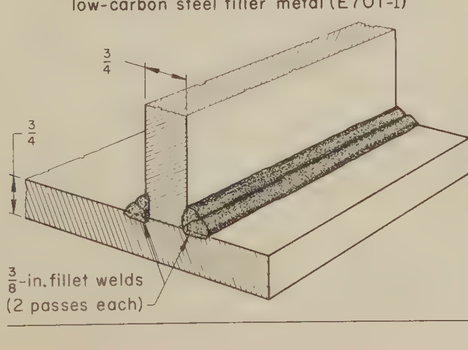
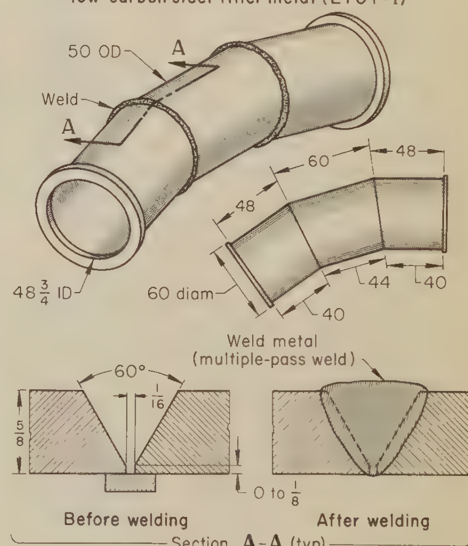
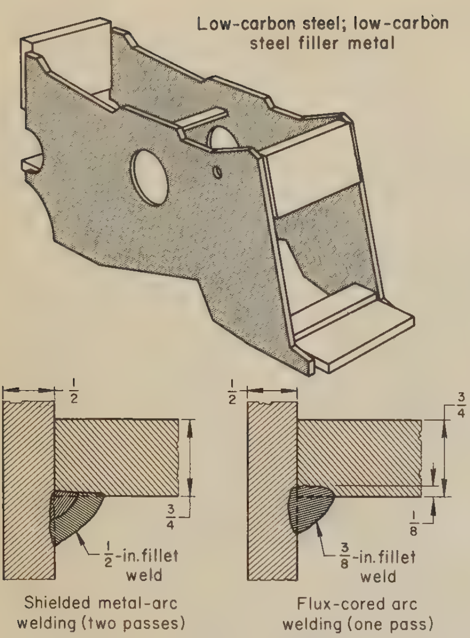


Table 15. Conditions and Costs for Welding Mitered Joints in Pump Casings by the Flux-Cored Arc Process With Auxiliary Gas Shielding (Example 25)

Welding Conditions	
Joint type	Butt
Weld type	60° single-V groove
Fixture	Rotating positioner
Position	Horizontal rolled
Number of passes	Five
Preheat	70 F
Shielding gas	Carbon dioxide, at 45 cfh
Electrode	3/32-in.-diam E70T-1
Electrode holder	500 amp, air cooled
Electrode-feed rate	160 ipm, all passes
Electrical stickout	1 to 1¼ in.
Power supply	600-amp constant-voltage rectifier
Current	420 to 440 amp, dcrp, all passes
Voltage	29 to 30 v
Travel speed	16 ipm
Postheat	Stress relieve
Cost Data	
Metal deposited, lb per ft	1.38
Deposition rate, lb of metal deposited per arc-hr	13.5
Operator efficiency, arc-hr per man-hr	33%
Electrode cost, per lb of metal deposited	$0.33
Shielding gas cost, per lb of metal deposited	$0.01
Labor and overhead rate, per hour	$10.00
Total cost per man-hour	$11.51
Total cost per foot of weld	$3.56

Low-carbon steel (ASTM A285, grade C); low-carbon steel filler metal (E70T-1)





Item	Shielded metal-arc welding	Flux-cored arc welding
Joint type	Corner	Corner
Weld type	Fillet	Fillet
Weld size, in.	½	⅜
Number of passes	Two	One
Shielding gas	...	CO_2, at 50 cfh
Electrode type	E7024	Low-carbon flux-cored
Electrode diameter, in.	7/32	3/32
Production rate, pcs/hr	1⅞	5

Fig. 19. Joints in brake supports that were welded by shielded metal-arc welding and flux-cored arc welding, showing fillet size and joint penetration (Example 27)

Originally, the components were joined by shielded metal-arc welding. To obtain adequate joint penetration, two passes were needed and slag had to be removed after each pass. By this method, production rate was 1⅞ supports per hour.

By changing to flux-cored arc welding, depth of penetration was increased, and fillet size could be decreased to ⅜ in. from the original ½ in. The ⅜-in. fillet weld was made in a single pass. Production rate was increased to five supports per hour and electrode consumption was reduced 44%.

Typical joints are shown in Fig. 19, and other welding details for the two processes are given in the accompanying table.

Example 28. Flux-Cored Arc Welding With Auxiliary Gas Shielding vs Shielded Metal-Arc Welding for a Filter-Shell Assembly (Fig. 20)

A filter-shell assembly, shown in Fig. 20 without fittings and appurtenances, was a pressure vessel made of three major components: a flanged, dished head; a cylindrical shell; and a cast steel flange ring for mounting a door. The vessel was designed for a working pressure of 75 psi, and was fabricated in accordance with the ASME Code for Unfired Pressure Vessels.

Originally, the two circumferential joints and the longitudinal joint were butt welded by the shielded metal-arc process, using E7018 low-hydrogen electrodes. For this method, joint design consisted of a 60° V-groove with a 1/16-in. root face and a 1/16-in. root opening. The groove opened to the outside of the vessel, and a root pass and three filler passes were made from the outside. The root was then back gouged and welded from the inside. Travel speed was about 2 in. per minute. Electrode size and welding current were as follows:

	Electrode diam, in.	Current (dcrp), amp
Root pass	5/32	160
Three filler passes	3/16	200
Backing pass	5/32	160

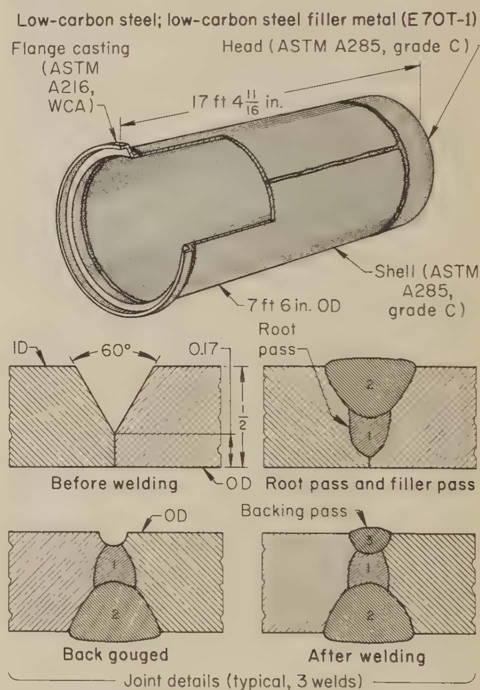
When welding of the filter shell was later changed to the flux-cored arc process, no additional tooling was required. Edges for the three joints were prepared by machining 30° bevels to a depth of approximately two-thirds the plate thickness so that, after fit-up, the 60° groove opened to the *inside* of the vessel. There were two reasons for doing this: (*a*) the weld puddle had high fluidity, and this could be controlled better if a major fraction of the welding could be done in flat position at the bottom interior of the vessel where the walls sloped upward, rather than at the top of the vessel where the walls sloped downward; and (*b*) back gouging of the root bead could be done by the air carbon-arc method more conveniently on the exterior of the vessel than on the interior, where flying sparks would interfere with the operation. With the flux-cored electrode, only one root pass and one filler pass were needed to fill the groove. The root-pass bead was back gouged and the final backing pass was made (Fig. 20).

All three joints on the vessel were essentially the same. The neck of the flange ring was tapered to shell thickness at the joint. On the head, to meet thickness requirements at the knuckle radius, where thinning occurred during forming, the material at the joint was slightly more than ½ in. thick, but the greater thickness was not enough to affect welding. Details of the welding procedure are given with Fig. 20. Travel speeds for the three passes were 18, 12 and 9 in. per minute, respectively. The travel speed for the completed joint was computed to be 4 in. per minute, or twice that of the shielded metal-arc method.

Major operations in fabricating the vessels were as follows. After layout, resquaring and beveling, the shell plate was rolled to size and tack welded. The head and the flange ring were then fitted and tack welded, and the vessel was checked for roundness. Welding was done as described above. All weld beads were carefully wire brushed, inspected for soundness, and repaired if necessary. Vessel openings, fittings, supports and inside track rails were then fitted and welded in place. Next, the vessel was stress relieved and checked for roundness, and the door was mounted to the flange ring and sealed. A hydrostatic test of 115 psi was applied, after which the vessel was cleaned and coated.

Examples 29 to 31. Flux-Cored Arc Welding Without Auxiliary Gas Shielding vs Shielded Metal-Arc Welding for Fillet Welds (Table 17)

A manufacturer of welded steel plate products reviewed welding procedures for



Conditions for Flux-Cored Arc Welding

Joint type	Butt
Weld type	60° V-groove
Welding position	Flat
Preheat	None
Shielding gas	Carbon dioxide, at 45 cfh
Electrode	5/64-in.-diam E70T-1
Electrode holder	300 amp, air cooled
Power supply	500-amp rectifier, slope control
Postheat	Heat in a furnace to 1050 to 1100 F, hold ½ hr, furnace cool

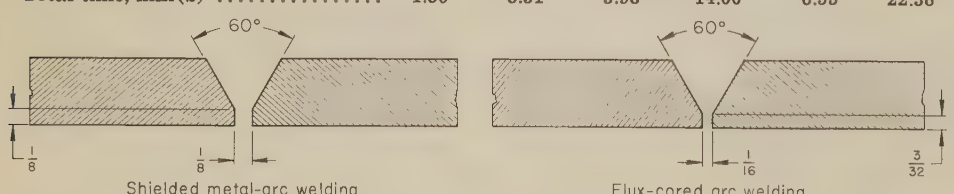
	Root pass	Filler pass	Backing pass
Electrode feed, ipm	172	176	176
Current, amp	300	340	340
Voltage, v	29	32	32
Travel speed, ipm	18	12	9

In shielded metal-arc welding (the process originally used), the first passes were made on the outside of the vessel, and the backing pass was made on the inside; the groove for each joint opened to the outside of the vessel, and had a 1/16-in. root opening.

Fig. 20. Filter shell (pressure vessel) that was flux-cored arc welded, using the joint design shown (Example 28)

Table 16. Conditions for Making Vertical Welds by Shielded Metal-Arc Welding (SMAW) vs Semiautomatic Flux-Cored Arc Welding (FCAW) With Auxiliary Gas Shielding (Example 26)

Item	Thickness of plate, in. ¼ FCAW	¼ SMAW	⅜ FCAW	⅜ SMAW	½ FCAW	½ SMAW
Number of passes	Two	Two	Two	Three	Two	Four
Electrode	E70T-1	E6010	E70T-1	E6010	E70T-1	E6010
Electrode diameter, in.	0.045	⅛	0.045	⅛;5/32(a)	0.045	⅛;5/32(a)
Current (dcrp), amp:						
1st pass	220	80	220	80	220	80
2nd pass	220	80	170	96	170	96
3rd pass	...	...	...	96	...	96
4th pass	...	...	...	...	...	110
Arc time, min	1.46	5.92	3.58	10.87	5.90	17.53
Electrode-change time, min	None	0.96	None	1.48	None	2.16
Cleaning time, min	0.40	1.43	0.40	1.65	0.65	2.69
Total time, min(b)	1.86	8.31	3.98	14.00	6.55	22.38



(a) ⅛ in. for first pass only. Remainder of passes, use 5/32-in. electrodes. (b) All times based on making a 12-in.-long weld in each thickness.

fillet welds. All fillet welds were being made by shielded metal-arc welding. Three types of semiautomatic welding were initially considered: gas metal-arc, flux-cored arc with carbon dioxide shielding, and flux-cored arc without auxiliary gas shielding. After reviewing costs of equipment, shielding gas, welder training, and portability and operability in the field, it was decided to limit the comparative study to flux-cored arc welding without auxiliary gas shielding and shielded metal-arc welding.

Two important objectives of the investigation were to determine the actual length of weld that could be deposited per hour, and the amount of electrode consumed per foot of weld, for the two processes. To do this, three types of joints commonly used in shop fabrication were selected. Joints of each type were welded by the two processes and data pertinent to the comparison were recorded. Shielded metal-arc welding was done according to the procedures then in use in the shop. Flux-cored arc welding was done using electrodes of the same size and type, and essentially the same current and electrode-wire feed rate, for all three joints.

Example 29 — T-Joint. A T-joint in ¼-in. plate was selected for this test. The requirement was to deposit a single ¼-in. fillet weld in the flat position, as shown in the view for this example in Table 17. When arc-time studies were made, a special electric clock was hooked up with the welding circuit, and an "operator factor", which reflected the time a welder spent depositing metal as compared to his total time, was derived. The operator factor was important in this comparison because when the shielded metal-arc process was used considerable time was spent in changing covered electrodes and restriking the arc.

The actual number of feet welded per hour (on the average) was obtained by converting welding speed in inches per minute to feet per hour and multiplying by the operator factor. Flux-cored arc welding produced more than three times as much weld per hour as shielded metal-arc welding.

For the flux-covered electrodes, electrode consumption in pounds per foot of weld was obtained by dividing the consumption in inches of weld per electrode by 12 to obtain feet of weld per electrode and dividing this figure into the weight of one electrode. For the continuous flux-cored electrode wire, consumption in pounds of electrode per foot of weld was obtained by multiplying the number of pounds purchased by 85%, the electrode-deposition efficiency usually accepted for flux-cored electrodes.

Example 30 — Corner Joint. For this joint, strength was of minor importance. The joint, which is often used in box construction, consisted of two ¼-in. plates assembled at a right angle, with the inside-corner edges touching so as to form a 90° groove, which was filled by welding (see Table 17).

Welding was done in the flat position. This type of weld is often used in low-stress applications. The iron-powder E7024 electrode selected for shielded metal-arc welding is intended for high-speed fillet welding. The data shown in Table 17 for this weld were obtained in the same manner as described in Example 29.

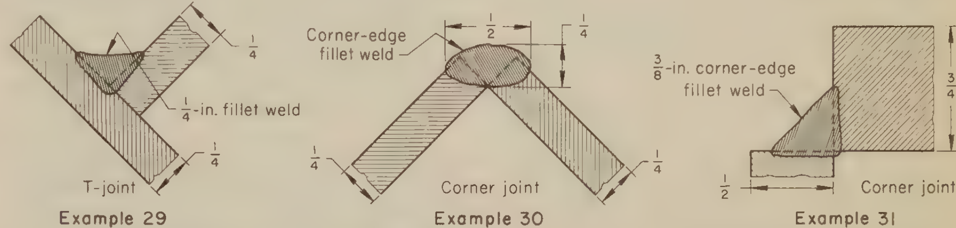
The production rate for flux-cored arc welding, expressed as actual feet welded per hour, was twice that obtained for shielded metal-arc welding.

Example 31 — Corner Joint. The corner joint for this comparison called for a ⅜-in. horizontal fillet weld as shown in the view for Example 31 in Table 17, and was made between plates ½ and ¾ in. thick. For shielded metal-arc welding, the low-hydrogen iron-powder E7018 electrode was selected because of its resistance to underbead cracking in higher-strength steels. Because of the thicker sections involved, cooling rate for the weld was higher than in the two previous examples. Three passes were required to fill the joint. The same type of electrode was used for each pass. The data shown for this weld were obtained in the manner described in Example 29. Production rate for flux-cored arc welding was three times that obtained for shielded metal-arc welding.

Because the types of joints described in Examples 30 and 31 are generally used in applications involving low stress, strength tests and quality inspection were not made.

Table 17. Production Rate, Electrode Consumption and Welding Variables for Fillet Welds Made by Shielded Metal-Arc Welding (SMAW) vs Flux-Cored Arc Welding (FCAW) Without Auxiliary Gas Shielding (Examples 29 to 31) (a)

Item	Example 29 — T-joint FCAW	SMAW	Example 30 — Corner joint FCAW	SMAW	Example 31 — Corner joint FCAW	SMAW
Welding position	Flat	Flat	Flat	Flat	Horizontal	Horizontal
Number of passes	One	One	One	One	One	Three
Electrode type	E70T-4	E7014	E70T-4	E7024	E70T-4	E7018
Electrode diameter, in.	³⁄₃₂	³⁄₁₆	³⁄₃₂	⁵⁄₃₂	³⁄₃₂	³⁄₁₆
Electrode length, in.	Continuous	14	Continuous	24	Continuous	14
Current, amp	350; dcrp	215; ac	325; dcrp	170; ac	350; dcrp	225; dcrp
Voltage, v	31	(b)	30	(b)	31	(b)
Electrode-feed rate, ipm	126	6.5	126	11	126	9.5
Length of weld per electrode, in.(c)	...	10.5	...	20.5	...	10.25
Operator factor, %(d)	50	35	50	35	50	35
Welding speed, ipm	18	6.5	25.5	16.2	8.85	4(e)
Welding speed, ft per hour (actual)	45	11.4	63.75	31.85	22.1	7(e)
Electrode consumption per foot of weld, lb	0.171	0.191	0.133	0.133	0.346	0.480



(a) Power consumption was not considered, because it was not significant. (b) Not metered. (c) For covered electrodes only. Takes into account average stub loss of 2 in. per electrode. (d) Average; arc time divided by man-hours times 100. (e) For three passes.

Examples 32 to 44. Flux-Cored Arc Welding With Auxiliary Gas Shielding vs Shielded Metal-Arc Welding for 13 Different Applications (Table 18)

For each of the 13 applications listed in Table 18, shielded metal-arc welding had been used, and the process was changed to flux-cored arc welding, at a substantial saving in welding time, generally from 35 to 50%. Continuous electrode feed, higher deposition rate, and faster travel speed were mainly responsible for the decreased welding time. Also, better visibility of the weld to the welder helped save time and improve weld quality.

Details about the work metal, the type of weld, and welding conditions for auxiliary-gas-shielded flux-cored arc welding are included in Table 18.

Table 18. Operating Conditions for 13 Applications of Auxiliary-Gas-Shielded Flux-Cored Arc Welding (Examples 32 to 44) (a)

Example number	Workpiece	Work metal	Size and type of weld	Electrode diameter, in.	Current (dcrp), amp	Voltage, v	Power supply rating, amp	Flow rate of CO_2 shielding gas, cfh	Travel speed, ipm
32	Semitrailer frame	Low-carbon steel	¼ to ⅜-in. fillet	³⁄₃₂	450	28	500	35	35 to 45
33	Press gear	1020 to 1045 steel	½-in. fillet	³⁄₃₂(b)	600	32	600	45	10
34	River-barge bottom	¼-in. low-carbon steel	Butt; seam	³⁄₃₂	400	27	500	35 to 40	60
35	Condenser shell	¼-in. low-carbon steel	Butt; pretacked	³⁄₃₂	250 to 280	25	500	35	41
36	Bulldozer blade	High-strength low-alloy steel	¼ and ⅜-in. fillet(c)	⅛	425 to 500	27 to 29	500	35 to 40	14 to 21
37	Mine car	½-in. low-carbon steel	V-groove butt; fillet(d)	⅛	450	30	500	45	...
38	Vibrator trough	½-in. low-carbon steel	Horizontal fillet(e)	³⁄₃₂	400	27	500(a)	45	...
39	Concrete pile boxes	⅝-in. low-carbon steel	Fillet	⁵⁄₆₄	380	30	500	35 to 40	13
40	Press gear	1020 to 1045 steel	V-groove, fillet	⁷⁄₆₄	600 to 700	32 to 34	750	35 to 40	(f)
41	Coiling spool	1¼-in. low-carbon steel(g)	Double-V; butt; seam(h)	⅛	650	30	900	25	...
42	Crown assembly	1½ to 2½-in. low-carbon steel	Fillet; T-joint	⅛	425	29	500	35 to 40	13(j)
43	Pipe-straightener frame	2 to 6-in. low-carbon steel	(k)	⅛	500	30 to 35	500	45 to 50	...
44	Press side section	4-in. low-carbon steel	Double-V; butt(m)	⅛	625	33	500	40 to 50	12 to 14(n)

(a) A constant-voltage motor-generator was used for all examples except No. 38, where a rectifier was used. (b) Electrode was in an automatic electrode holder mounted on a manipulator. (c) A positioner was used, and welding was in both flat and horizontal positions. (d) Fillets welded in both flat and horizontal positions. (e) Welded in flat position. (f) Metal deposition was 24 lb per hour. (g) Plate was rolled to 24-in. diameter. (h) Welded in flat position. (j) On a 1-in. fillet weld. (k) Double-V-groove and single-V-groove welds and double-fillet welds, in the flat and horizontal positions. (m) Longitudinal seam. (n) For first and second passes. Third and final passes were at 6 ipm.

Flux-Cored Arc Welding vs Gas Tungsten-Arc Welding. Gas tungsten-arc welding is not extensively used for welding carbon and low-alloy steels, although there are applications in which it has proved advantageous. The example that follows describes an application in which replacement of gas tungsten-arc welding by flux-cored arc welding resulted in improved weld quality and higher production.

Example 45. Flux-Cored Arc Welding vs Gas Tungsten-Arc Welding for Better Quality and Faster Welding (Fig. 21)

The three 4-by-6-in. blocks of ⅜-in.-thick 1020 steel shown welded to a vault door in Fig. 21 served as guides for the closing mechanism of the door. The door slab, also of 1020 steel, was 30 in. wide, 60 in. long and 4 in. thick. The frame, of 1-in.-square 1020 steel bars (see Fig. 21), had been joined to the door by shielded metal-arc corner and peripheral fillet welds as described in Example 11.

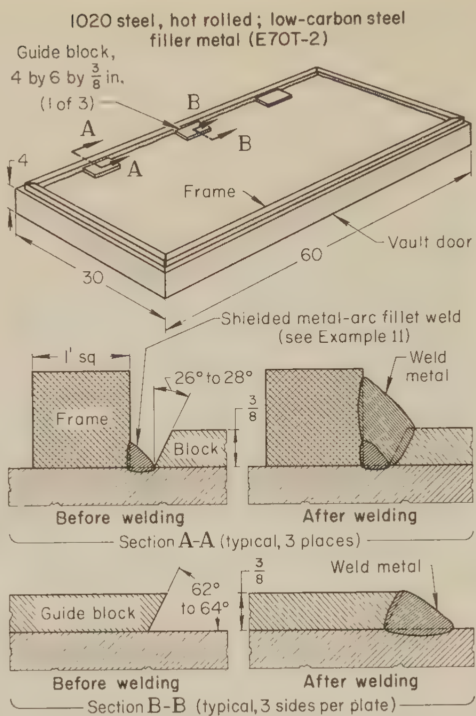
Originally, gas tungsten-arc welding with a low-carbon steel filler metal was used for joining the guide blocks to the frame and door, because this process seemed suitable to the six short welds (involving two welding positions and several changes in direction) that were required for each guide block.

However, experience revealed two drawbacks to this procedure: (*a*) excessive weld porosity, and (*b*) the length of time required to weld a guide block (14 to 16 min).

To overcome these shortcomings, flux-cored arc welding with carbon dioxide shielding was tried and eventually adopted. All six joint edges of the blocks were beveled 26° to 28° by milling without a cutting fluid (to eliminate a cleaning operation). Toggle clamps were used to hold the blocks during welding to maintain a ±0.005-in. tolerance on alignment of drilled holes. Each guide was completed before welding was started on the next guide block.

Results were satisfactory. Welds were uniformly sound, and welding time per guide block was reduced to 1½ min. Cleaning to remove slag and weld spatter was minimal. Some finish grinding was required, to remove rough spots that appeared occasionally where the weld changed direction.

Details for flux-cored arc welding are given in the table that accompanies Fig. 21.



Conditions for Flux-Cored Arc Welding

Joint type	Butt and lap
Weld type	Groove, with fillet reinforcement
Welding position	Horizontal (4 sides); vertical (2 sides; joints not shown in illustration)
Number of passes	One
Preheat	None
Fixtures	Toggle clamps
Shielding gas	Carbon dioxide, at 30 psi
Electrode	⅛-in.-diam E70T-2
Electrode-feed rate	325 to 350 ipm
Power supply	Rectifier, high/low ranges
Current	350 to 375 amp, dcrp
Welding time per guide block	1½ min

Originally, the guide blocks were welded by the gas tungsten-arc process, but welds were porous and welding time per block was ten times that for flux-cored arc welding.

Fig. 21. Vault door with three guide blocks that were joined to door and frame by flux-cored arc welding (Example 45)

Flux-Cored Arc Welding vs Submerged-Arc Welding. These two welding processes are often competitive (see Example 21). Both are capable of high deposition rates and deep joint penetration, although flux-cored arc welding with auxiliary gas shielding usually penetrates deeper. Weld position and length of weld often influence the choice of process. The example that follows describes an application where flux-cored arc welding with auxiliary gas shielding proved more satisfactory.

Example 46. Flux-Cored Arc Welding With Auxiliary Gas Shielding vs Submerged-Arc Welding for Tube-and-Gland Assemblies (Fig. 22)

The tube-and-gland assembly shown in Fig. 22 served as a liner in a cylinder used for pumping abrasive materials such as coal and crushed ore. Joining the gland to the liner tube called for two circumferential partial-penetration groove welds.

Originally, welding was done by the automatic submerged-arc process. The two components were rough machined for a loose fit (0.035-in. clearance) to allow for shrinkage. The joint was prepared for welding by machining the gland as shown in the "Original method" in Fig. 22, and then both the tube and the gland were cleaned with a detergent. The liner and gland were assembled in a rotatable chuck, with the tube axis at an angle of 20° from vertical. No tack welding was needed. Three weld passes were made by rotating the assembly under a stationary electrode holder. Continuous rotation was made possible by mounting an air chisel directly behind the electrode holder, to remove the slag as welding progressed. The workpiece was then turned end for end and the second weld was made by the same procedure. No preheat was used, but the part was stress relieved after welding and prior to final machining, which included removal of the weld reinforcement. Details of the welding operation are given in the table with Fig. 22. Joints were examined for cracking, visually and by magnetic-particle inspection.

Submerged-arc welding was too slow, because to obtain required strength, fill, and joint penetration it was necessary to use a joint that entailed preparation of two surfaces and that had to be welded in three passes. Moreover, about 5% of the weldments were rejected because of defects, and required repair.

To increase production, the joint was redesigned for flux-cored arc welding. The weld groove was changed to the 45° bevel shown for "Improved method" in Fig. 22. As a result, the flux-cored arc process could be used to complete the weld in one pass. The simpler joint design was not suitable for submerged-arc welding because it would not allow sufficient penetration. Flux-cored arc welding completed the single weld pass required in 1½ min arc time, whereas the submerged-arc process required three passes with an average arc time of 1¾ min per pass (5¼ min total).

In addition to obtaining a reduction in arc time of over two-thirds, the welds were more uniform and the rejection rate dropped to an average of 0.75%. Over-all saving in production cost was estimated at 50%. Fixtures for flux-cored arc welding were essentially the same as those used for submerged-arc welding. Conditions for welding by both processes are given in the table accompanying Fig. 22.

APPENDIX

Composition and Selection of Flux-Cored Electrodes

By D. C. SMITH*

FLUX-CORED electrodes for surfacing applications date back beyond the 1930's and thus are not a modern development. They were originally used with what was known as the "open-arc" process, with no auxiliary gas shielding of the weld metal. Their diameter sizes were usually 5⁄64 in. and larger, so the feeding problems that develop with smaller electrode wires were never encountered. The methods now employed with flux-cored electrodes for general fabrication are relatively new.

The general use of flux-cored electrodes externally shielded by carbon dioxide began in the United States in the early 1960's, and there has been a steady growth, the growth rate being considerably greater for the auxiliary-shielded electrodes than for the self-shielding electrodes.

Classification. Nine types of flux-cored electrode wires are covered by AWS A5.20-69 (see Tables 1 and 2, page 26). Characteristics of the nine types are described on page 27. In the AWS specification, there has been no attempt to classify flux-cored electrodes according to the type of material in the core, as is done with the coverings on electrodes for manual shielded metal-arc welding.

Flux-Cored Electrodes for Use With Auxiliary Carbon Dioxide Shielding

The fluxes in flux-cored electrodes for use with auxiliary carbon dioxide shielding are of three types, which we will designate as:

1 High-titania
2 Lime-titania
3 Lime.

In the first (high-titania) type, the slag and weld-metal characteristics are somewhat similar to the E7014, E7024 and E6013 types of covered electrodes for shielded metal-arc welding. The principal difference lies in the depth of penetration of the weld and the absence of hydrogen-forming compounds in the flux core. Covered electrodes have much shallower penetration, whereas the flux-cored electrodes for carbon-dioxide-shielded welding provide deep penetration, permitting a much smaller fillet weld with the same throat thickness.

*Welding consultant. This Appendix is a condensation of Dr. Smith's article in *Welding Journal*, July 1970, pages 535 to 547.

The second (lime-titania) type of flux-cored electrode is comparable to the formerly used covered electrode designated as the lime-ferritic low-hydrogen type, which contained about 8% titanium dioxide along with high fluorspar and some carbonate in the flux. This type forms a basic slag but contains some titanium dioxide slag-forming compounds. The calcium compounds, especially fluorspar, are less, but the volume of slag is usually greater than for all-basic slag of type 3.

The third (lime) type of flux-cored electrode forms a basic slag and contains no titanium dioxide slag-forming compounds and only a small amount of silicon dioxide slag-forming compounds.

Type 1 (high-titania) was the first type developed for use with auxiliary carbon dioxide shielding and has the highest welder appeal. This type has low spatter, smooth bead, good penetration, and deposits fillets of excellent shape. Horizontal fillets are nearly flat and positioned fillets are slightly concave. Weld-metal compositions (manganese and silicon) and mechanical properties of all-weld-metal specimens deposited from four brands of type 1 electrode are given in Table 19.

Type 2 (lime-titania) has good arc stability and fairly low spatter and, in general appearance, falls between the titania type and the lime type but closer to the lime type. Horizontal fillets from lime-titania electrodes show a slight rollover on the lower leg, and positioned fillets have a slight convexity. Type 3 (lime) shows more rollover on the lower leg of a horizontal fillet and more convexity in a positioned fillet. Although it may be difficult to differentiate between types 2 and 3 by the shape of their fillets, it is easy to differentiate type 1 from the other two types by fillet shape.

Because no hydrogen-bearing compounds are used in the fluxes and the shielding is done with carbon dioxide gas, all of these flux-cored electrodes are classed as low-hydrogen. Some of the lubricants used when the electrode is coiled may be a source of the small amount of hydrogen liberated in the welding arc. (Generally, drawing compounds are baked off from the finished drawn wire, and a light coat of lubricant is applied during coiling.)

Although type 1 (high-titania) electrodes can be designated as low-hydrogen, as explained above, these electrodes do not yield weld deposits of the same quality as the common low-hydrogen covered electrodes for shielded metal-arc welding. Also, type 1 does not have a basic-type slag like the low-hydrogen covered electrodes, whereas types 2 and 3 do.

The AWS specification does not differentiate among these three types. The third type may be classed as E70T-5, if it is used without auxiliary gas, and the other types may be classified as E70T-1 if they are multiple-pass electrodes, or as E70T-2 if they are single-pass electrodes. This results in some confusion to the user, because he may have several types of one brand falling in the same classification. For example, most manufacturers make three or four electrodes of the high-titania type (E70T-1), varying the manganese and silicon contents of the weld metal (Table 19). Both type 2 and type 3 may be classed in the E70T-1 category, making it difficult for the user to order by classification rather than brand.

Table 19. Manganese and Silicon Contents and Mechanical Properties of Weld Metal From Four Brands of E70T-1 Electrodes

Brand	Mn, %	Si, %	Mechanical properties TS, psi	YS, psi	El, %	RA, %
A	0.85	0.40	75,000	65,000	25	61
A1 ...	1.20	0.60	85,000	75,000	28	60
A2 ...	1.35	0.33	85,000	76,000	30	62
A3 ...	1.65	0.75	95,000	85,000	25	60

This same confusion exists with the fluxes in alloy steel electrodes. Because of the low hydrogen content of the arc, a high-titania-type flux can be used successfully with low-alloy high-tensile weld metal. However, if maximum notch toughness along with maximum resistance to cracking (either hot or cold) is desired, this is not the best flux to use.

In countries outside the United States, most flux-cored alloy steel electrodes are made with the basic (lime-type) flux, and a titania-type flux is used only for welding mild steel. For making critical welds in alloy steel with flux-cored electrodes, manufacturers in this country are reverting to the basic (lime-type) flux, even though weldability suffers somewhat.

To combine low hydrogen content with a basic-type flux gives the best slagging medium, particularly in welding steel of high tensile strength. It is not known exactly what function calcium performs, but it is quite well confirmed that a beneficial effect results from the presence of only a small percentage of calcium. A small content of calcium appears to have a favorable influence on the solidification process, on ferrite and cementite formation, and on bulk properties of ferrite.

Calcium fluoride is one of the best fluxing and scavenging mediums known to designers of electrodes; the presence of this compound, together with calcium carbonate, results in a basic slag, which in turn is responsible for the better quality of weld metal, as measured by notch toughness and resistance to cracking.

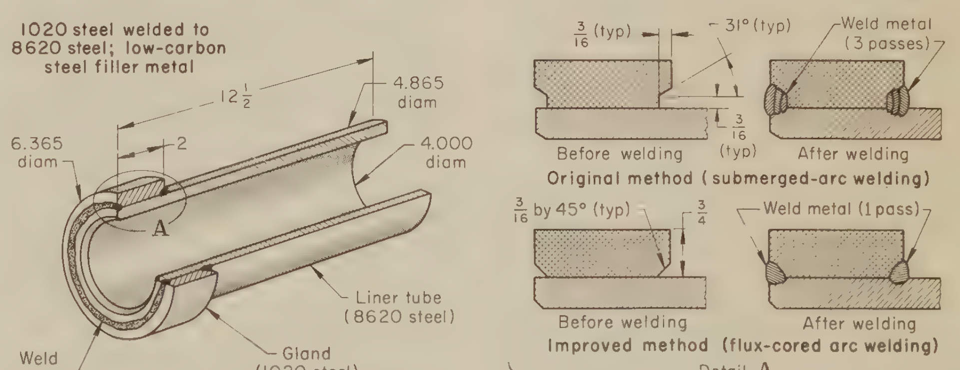
Typical flux and slag compositions of the three types of flux-cored electrodes used with carbon dioxide shielding are given in Table 20. These three types correspond to AWS classifications as follows:

Type 1 (high-titania) E70T-1 or E70T-2
Type 2 (lime-titania) E70T-1
Type 3 (lime) ....E70T-1 or E70T-5

The compounds given in Table 20 can be added to the flux core by various means. For example, silicon dioxide may be added as one of the many natural silicates, as pure sand, as ground glass, or as ferrosilicon. Each brand may vary somewhat in the percentage of these constituents. The main difference is the high titanium dioxide and silicon dioxide contents of the high-titania type as compared to the other types, and the high content of calcium oxide in the two basic types, as compared to virtually no calcium oxide in the high-titania type.

The types designated as lime-titania have properties intermediate between those of the high-titania and high-lime types and may be used where both appearance and quality are desired. However, where the greatest resistance to cracking and the highest notch toughness at low temperature are desired, the lime type (all-basic) is usually the best choice.

The lime type has another advantage: it is less sensitive to the carbon dioxide shielding and thus will be affected less readily by air currents created by fans or by open-field air circu-



	Submerged-arc welding	Flux-cored arc welding
Number of passes	Three	One
Welding position	Horizontal; 20° off vertical	Horizontal; 20° off vertical
Preheat	None	None
Shielding	Flux	Carbon dioxide, at 40 cfh
Fixture	Rotating chuck	Rotating chuck
Electrode	0.120-in.-diam E8018-B2 (equiv.)	0.120-in.-diam flux-cored
Electrode holder	Fixed	400 amp, water cooled, fixed
Electrode feed, ipm	50 (est)	135 (est)
Electrical stickout, in.	1½	1
Power supply	500-amp rectifier	500-amp rectifier
Current (dcsp), amp	440	300
Voltage, v	33	33
Postheat	1250 F, 2 hr	1250 F, 2 hr
Travel speed, ipm	9.1 (avg)	10.5
Production time (arc time)	5¼ min per part	1½ min per part

Fig. 22. Liner-and-gland assembly for which flux-cored arc welding resulted in a higher production rate than submerged-arc welding. Joint designs and completed welds for both processes are shown at the right. (Example 46)

Table 20. Typical Flux and Slag Compositions for the Three Types of Carbon-Dioxide-Shielded Flux-Cored Electrodes

Compound or element	Type 1 High-titania (nonbasic) Flux	Slag	Type 2 Lime-titania (basic or neutral) Flux	Slag	Type 3 Lime (basic) Flux	Slag
SiO_2	21.0%	16.8%	17.8%	16.1%	7.5%	14.8%
Al_2O_3	2.1	4.2	4.3	4.8	0.5	...
TiO_2	40.5	50.0	9.8	10.8	...	...
ZrO_2	...	...	6.2	6.7	...	...
CaO	0.7	...	9.7	10.0	3.2	11.3
Na_2O	1.6	2.8	1.9	...	...	...
K_2O	1.4	...	1.5	2.7	0.5	...
CO_2	0.5	...	...	...	2.5	...
C	0.6	...	0.3	...	1.1	...
Fe	20.1	...	24.7	...	55.0	...
Mn	15.8	...	13.0	...	7.2	...
CaF_2	...	...	18.0	24.0	20.5	43.5
MnO	...	21.3	...	22.8	...	20.4
Fe_2O_3	...	5.7	...	2.5	...	10.3
Flux	13	...	13	...	27	...
AWS classification	E70T-1 or E70T-2		E70T-1		E70T-1 or E70T-5	

Table 21. Mechanical Properties and Chemical Compositions of Weld Metal From an Alloyed Basic Flux-Cored Electrode With and Without Carbon Dioxide Shielding

Shielding	Mechanical properties TS, psi	YS, psi	El, %	RA, %	Weld-metal composition, % C	Mn	Si	Ni	Mo
CO_2	109,000	91,500	26	64	0.07	1.63	0.45	1.54	0.34
None	120,000	99,500	18	36	0.08	1.84	0.57	1.72	0.37

Shielding	Temperature, F	Charpy V-notch impact, ft-lb						X-ray quality
CO_2	−60	38	33	33	39	38	36 avg	Good
None	−60	30	33	33	30	32	32 avg	Fair (some slag)

Table 22. Mechanical Properties and Chemical Compositions of Weld Metal From Mild Steel Basic Flux-Cored Electrodes With Different Types of Shielding

Shielding	Mechanical properties TS, psi	YS, psi	El, %	RA, %	Weld-metal composition, % C	Mn	Si
CO_2, 40 cfh	79,400	67,300	28	66	0.07	1.43	0.44
100% argon	90,000	81,300	28	62	0.06	1.65	0.50
No shielding	90,000	77,500	25	53	0.06	1.56	0.49

Shielding	Temperature, F	Charpy V-notch impact, ft-lb			
CO_2	0	163	120	123	136 avg
CO_2	−20	86	68	91	81 avg
CO_2	−60	41	35	27	34 avg
100% argon	−60	28	24	19	24 avg
No shielding	−60	17	18	12	16 avg

Table 23. Chemical Compositions of Slag From a Mild Steel Basic Flux-Cored Electrode With Different Types of Shielding

Chemical compound	CO_2, at at 40 cfh	100% argon, 40 cfh	No shielding
SiO_2	8.7%	4.7%	7.0%
Al_2O_3	0.03	0.0	0.9
TiO_2	7.6	10.7	9.0
CaO	7.3	6.4	3.8
MgO	0.6	0.9	1.1
Na_2O	0.7	1.0	1.1
CaF_2	59.4	66.3	62.5
MnO_2	4.8	3.7	3.6
Total C	0.01	...	...

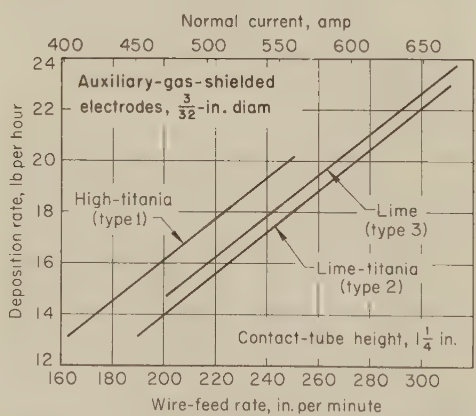


Fig. 23. Effect of wire-feed rate on deposition rate for the three types of auxiliary-gas-shielded flux-cored electrodes

lation. Some of these types can operate satisfactorily without auxiliary gas shielding if an electrical-contact-tube height (stickout) of 2½ to 3 in. is used. When trying to use the electrode without auxiliary gas shielding with this longer electrical-contact-tube height, however, penetration of the weld metal will decrease and slag may be trapped and show up as defects in radiographic inspection. The mechanical properties of the weld metal likewise will not be the same. Table 21 illustrates the difference for an alloy steel brand of this type of electrode with and without auxiliary gas shielding.

Table 22 gives the results obtained with one brand of mild steel basic-type flux-cored electrode with and without auxiliary gas shielding. This table shows the decrease in manganese and silicon contents with a corresponding decrease in tensile and yield strengths and an increase in notch toughness as the type of shielding is changed. Argon shielding gas protects the manganese, silicon and carbon from oxidation as the metal transfers across the arc. In the self-shielding transfer of weld metal, some of the manganese, silicon and carbon are oxidized in the arc, resulting in lower amounts in the weld metal. When carbon dioxide is used as shielding gas, manganese, silicon and carbon are oxidized still more, further decreasing these elements in the weld metal.

Table 22 also shows an increase in tensile strength with increase in manganese and silicon, and a corresponding drop in low-temperature Charpy impact values when welding is done without carbon dioxide shielding. Welding with argon gas increases the manganese and silicon in the weld-metal deposit above that produced by welding with no gas shielding or with carbon dioxide shielding. This result is to be expected because of the oxidizing effect of carbon dioxide shielding and the atmospheric oxidizing effect of no gas shielding on the manganese and silicon contents. The tensile and yield strengths increase proportionately as these alloying elements increase, and the notch toughness increases to an optimum and then decreases.

The chemical composition of the slag from a flux-cored basic (type 3) mild steel electrode when using different types of shielding is given in Table 23. The table shows that argon shielding protects the manganese and silicon, which go into the weld metal instead of into the slag. With carbon dioxide shielding, more manganese and silicon are oxidized and go into the slag. In self-shielding flux-cored arc welding, manganese and silicon are oxidized more than would normally be expected, because the long electrical stickout heats the electrode to a higher temperature than the short stickout used in the carbon-dioxide-shielded type, which gives more exposure of the weld metal to atmospheric oxygen and nitrogen. However, the high volume of carbon dioxide surrounding the auxiliary-gas-shielded type is more oxidizing, resulting in at least as much reduction of manganese and silicon as when the self-shielding electrode is used with long stickout. For maximum retention of manganese and silicon in the weld metal, therefore, argon shielding is preferred.

A comparison of the deposition rates of the three types of electrodes that are shielded with carbon dioxide is shown in Fig. 23. These values were obtained on typical electrodes of three different brands in the amperage and voltage ranges recommended by the manufacturer. The center of the range represents the optimum condition recommended for the 3/32-in.-diam size. At optimum settings there is little difference in deposition rates. Type 3 (lime-type) shows slightly higher efficiency and deposition rate at the optimum setting; this can be attributed to the higher content of iron powder in the flux. Some brands in these classifications are designed for higher efficiencies and have higher deposition rates. For this article, however, the more common types were used to plot the curves.

Self-Shielding Flux-Cored Electrodes

Self-shielding flux-cored electrodes have sometimes been referred to as covered electrodes turned inside out. All the shielding must come from the flux on the inside of the metal sheath, whereas the covered electrode has the flux on the outside of the solid metal core. In most covered electrodes, the greatest amount of shielding is done by gases formed during the decomposition of the fluxes with the heat of the

electric arc. This method of shielding is effective, because the gas shield surrounds the weld metal as it enters the weld puddle.

Because flux-cored electrodes have the flux on the inside of the metal as it enters the weld puddle, gas-forming ingredients cannot be used effectively in the flux. Gas formers would increase weld spatter and push the metal out into the air instead of shielding the metal from the air. Therefore, other means of cleaning and shielding the weld metal from atmospheric contamination are required.

Four types of self-shielding flux-cored electrodes are available today (July 1970):

1 Fluorspar-aluminum
2 Fluorspar-titania
3 Fluorspar-lime-titania
4 Fluorspar-lime.

Most self-shielding electrodes marketed today are of the first and second types, with the third type next, and type 4 last. Type 4 may also be considered as a type 3 electrode for use with auxiliary carbon dioxide shielding and thus fall into classification E70T-5 of AWS A5.20-69, designed for use both with and without carbon dioxide shielding.

The principal difference in the use of all the self-shielding electrodes, in comparison with the electrodes used with auxiliary carbon dioxide shielding, is the electrode holder used by the welder. With most self-shielding flux-cored electrodes, an electrical-contact-tube height (stickout) from 2½ to 5 in. is required, whereas with carbon dioxide shielding, stickout of ¾ to 1 in. is required. The electrode holder designed for the self-shielding electrode has a hidden, insulated, contact-tube height of 1½ to 4 in., so the visible stickout is the same for both carbon-dioxide-shielded and self-shielding types.

A cutaway section of the two types of nozzles is given in Fig. 1, on page 78. The voltage requirements for the two are about the same. Because of the large difference in electrical stickout, however, the amperage will be much less for the self-shielding types, even though the electrode feed may be the same or higher. Details of these properties are discussed later in this article.

Typical compositions of the fluxes of the four groups of self-shielding flux-cored electrodes are given in Table 24. The percentages of the constituents vary depending on the amount of iron powder used and the thickness of the strip from which the tube is formed. The thickness of the strip determines the flux-steel ratio. For the samples given, the flux varied from 15 to 28%. The percentage of flux varies with different brands, but all that were checked fell within this range. Table 24 represents 12 different brands from five different manufacturers.

Table 24. Typical Flux and Slag Compositions for the Four Types of Self-Shielding Flux-Cored Electrodes

Compound or element	Type 1 Fluorspar-aluminum		Type 2 Fluorspar-titania		Type 3 Fluorspar-lime-titania		Type 4 Fluorspar-lime	
	Flux	Slag	Flux	Slag	Flux	Slag	Flux	Slag
SiO_2	0.5%	...	3.6%	0.2%	4.2%	1.8%	6.9%	0.2%
Al	15.4	...	1.9	...	1.4	...	...	...
Al_2O_3	...	11.8%	...	6.5	...	6.0	0.6	12.8
TiO_2	...	...	20.6	27.0	14.7	33.5	1.2	2.3
CaO	...	...	...	...	4.0	...	3.2	4.1
MgO	12.6	9.2	4.5	4.5	2.2	6.0	...	0.9
K_2O	0.4	...	0.6	1.8	...	...	...	...
Na_2O	0.2	...	0.1	1.0	...	...	0.6	0.9
C	1.2	...	0.6	...	0.6	...	0.3	...
CO_2	0.4	...	0.6	...	2.1	...	1.3	...
Fe	4.0	...	50.0	...	50.5	...	58.0	...
Mn	3.0	...	4.5	...	2.0	...	7.9	...
Ni	...	...	...	...	2.4	...	...	...
CaF_2	63.5	76.1	22.0	53.0	15.3	47.5	22.0	73.7
MnO_2	...	0.4	...	1.1	...	2.8	...	0.7
Fe_2O_3	...	2.5	...	1.9	...	3.6	...	3.0
Flux	18	...	18	...	26	...	26	...
AWS classification	E70T-4, E60T-7 or E60T-8		E70T-3		E70T-6		E70T-5	

Slag Characteristics and Mechanical Properties of Weld Metal Deposited From Self-Shielding Electrodes

As shown in Table 24, the slags formed from the four types of self-shielding electrodes differ considerably in chemical composition. The carbon and alloy contents of the weld metal deposited also may vary significantly (Tables 25 to 29), with consequent variations in mechanical properties.

Type 1 — Fluorspar-Aluminum. This type of flux-cored electrode is characterized by an aluminum-colored low-density slag that forms with the emission of a fairly heavy volume of smoke. The welding characteristics of the electrode are generally rated by welders as good, the greatest complaint being the heavy volume of smoke when welding is being done in unventilated areas. The appearance of the weld bead is generally very good, with the shape of horizontal fillet welds approaching a flat surface and with equal leg lengths. The weld metal feathers out well on both the upper and lower legs of horizontal and positioned fillet welds. Slag removal is generally good except when the weld metal is highly diluted with base metal. Such a condition may cause the slag to cling to the surface more tightly. Because of the high aluminum content of the weld metal, this electrode sometimes is not satisfactory for tacking joints together for subsequent welding. The weld metal does not arc-air gouge like other mild steel weld metal, so when the arc-air torch is used to smooth out the weld surface, more difficulty may be encountered than with other mild steel welds.

If the welder uses proper technique to avoid entrapment of slag, x-rays are generally water-clear. As with all types of self-shielding flux-cored electrodes, penetration is not nearly so good as with the auxiliary-gas-shielded types, primarily because of the long contact-tube height (3 in.), which consumes energy for preheating the electrode. On the other hand, the short contact-tube height (1 in.) allows this energy to go into the base metal, thus increasing the penetration to some extent.

The notch toughness of weld metal deposited from the fluorspar-aluminum type of self-shielding electrode is rather low. When used in a flat position and when the weld metal is alloyed with 0.50 to 0.75% nickel, Charpy impact values may be as high as 20 ft-lb at 0 F. The standard commercial electrode gives a lower notch toughness and falls in the AWS E70T-4 classification. When modified for higher notch toughness, it meets the E60T-8 classification.

Small-size electrodes of this type (5⁄64 in. in diameter and smaller) with some modification of the flux composition are designed for out-of-position welding. The stickout is generally 1¼ in. (similar to carbon-dioxide-shielding types); low voltage (18 to 22 volts) and straight polarity, with correspondingly low amperage, are used. Electrodes designed for this out-of-position application fall into the AWS E60T-7 classification. However, the quantity of electrodes used for such applications is small at present (1970).

Typical mechanical and chemical properties of weld metal deposited from electrodes of the fluorspar-aluminum type are given in Table 25 (E70T-4) and Table 26 (E60T-7).

In welding with electrodes of the fluorspar-aluminum type, metal transfer is globular, bordering on the spray type. With the smaller electrode sizes, transfer becomes spray type when straight polarity and 1 to 1¼-in. stickouts are used, as is common for out-of-position welding. The typical voltage and amperage requirements for the 5⁄64-

Table 25. Typical Mechanical and Chemical Properties of Weld Metal From Type 1 (Fluorspar-Aluminum) Self-Shielding Flux-Cored Electrodes (E70T-4)

Mechanical Properties of Weld Metal

Tensile strength	80,300 psi
Yield strength	56,500 psi
Elongation in 2 in.	26%
Reduction in area	55%
Charpy V-notch impact:	
75 F	25, 24, 26, 22 ft-lb
0 F	10, 10, 11, 11, 12 ft-lb

Weld-Metal Composition

Carbon	0.22%	Sulfur	0.012%
Manganese	0.81	Phosphorus	0.008
Silicon	0.14	Aluminum	1.5

Table 26. Typical Mechanical and Chemical Properties of Weld Metal From Type 1 (Fluorspar-Aluminum) All-Position Self-Shielding Flux-Cored Electrodes (E60T-7)

Mechanical Properties of Weld Metal

Tensile strength	88,300 psi
Yield strength	67,300 psi
Elongation in 2 in.	24%
Reduction in area	49%

Weld-Metal Composition

Carbon	0.20%	Sulfur	0.006%
Manganese	0.40	Phosphorus	0.006
Silicon	0.20	Aluminum	1.55

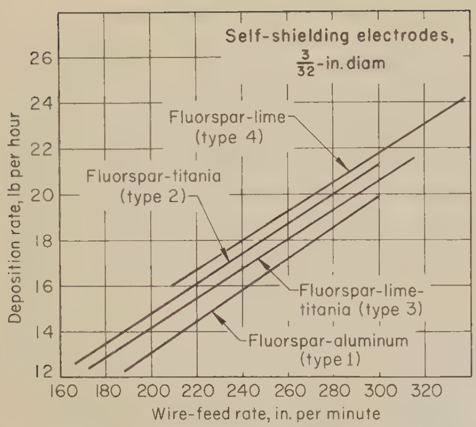


Fig. 24. Effect of wire-feed rate on deposition rate for the four types of self-shielding flux-cored electrodes

Table 27. Mechanical and Chemical Properties of Weld Metal From One Brand of Type 2 (Fluorspar-Titania) Self-Shielding Flux-Cored Electrode and Welding Conditions for Multiple-Pass and Sheet-Metal Applications

Mechanical Properties of Weld Metal	
Tensile strength	90,300 to 105,000 psi
Yield strength	78,000 to 87,000 psi
Elongation in 2 in.	20 to 15%
Reduction in area	60%
Weld-Metal Composition	
Carbon	0.08 to 0.12%
Manganese	0.80 to 1.10
Silicon	0.40 to 0.60
Sulfur	0.009 to 0.012
Phosphorus	0.008 to 0.012
Aluminum	0.05 to 0.15
Welding Conditions for Multiple-Pass Application	
Electrode size	3/32 in.
Current	350 amp
Voltage	29 v
Electrode feed	240 ipm
Welding Conditions for Sheet-Metal Application (0.089 to 0.119 In.)	
Electrode size	3/32 in.
Current	520 to 625 amp
Voltage	26 to 30 v
Electrode feed	220 to 275 ipm
Travel speed	110 to 200 ipm
Electrical stickout	3/4 to 1 in.

in.-diam electrode used for out-of-position welding are 18 to 22 volts and 150 to 250 amp.

Type 1 (fluorspar-aluminum) E70T-4 and E60T-8 electrodes are intended for welding both heavy and light sections, including machinery and machinery parts, structural fabrication, field erection, column splices, beam-to-column connections, and repair of heavy machinery. The E60T-7 electrodes, in 5/64-in. and smaller diameters, are designed for all-position welding, have similar flux compositions, and likewise fall into this same classification. Applications involving joints with poor fit-up and high-carbon, high-sulfur, and other difficult-to-weld steels are successfully welded with this type of electrode, provided the application does not require high notch toughness at low temperature. For vessels and structural work where compliance with rigid codes is necessary, the use of this type of electrode is generally restricted. Some brands are particularly well suited for high deposition rates.

Type 2 — Fluorspar-Titania. This type of self-shielding flux-cored electrode is characterized by a heavy, dense slag similar to that from type 3 electrodes and may or may not have a golden color on the underside of the slag. It is designed to yield a fast-follow weld metal, which makes it excellent for high-speed, usually automatic, welding of light metal frames. It is usually employed for single-pass fillet welds and is seldom used in multiple-pass applications. When used in high-speed welding, the electrical-contact-tube height is 3/4 to 1 in., using high amperage and moderate voltage.

Because this type of electrode is not designed for multiple-pass operation, few data on mechanical properties of the weld metal are published. Some brands of this type, when used in a multiple-pass operation with the usual long stickout technique, give fairly good mechanical properties. The chemical and mechanical properties of weld metal obtained from one brand when welding according to AWS A5.18-65T are given in Table 27.

Applications of type 2 electrodes generally are automatic operations involving high-speed welding, as in automotive frame welding. Short stickouts of 3/4 to 1 1/4 in. are used with travel speeds up to 200 in. per minute. Type 2 electrodes can also be successfully used for a single pass or for fillet welds of unlimited size in multiple passes. Likewise, heavy sections can be butt welded where service conditions do not require weld metal of high ductility and notch toughness; for welds for such service, the usual long stickout (2 1/2 to 3 in.) should be used.

Table 28. Mechanical and Chemical Properties of Weld Metal From Type 3 (Fluorspar-Lime-Titania) Self-Shielding Flux-Cored Electrodes

Mechanical Properties of Weld Metal	
Tensile strength	89,000 psi
Yield strength	78,000 psi
Elongation in 2 in.	29%
Reduction in area	65%
Charpy V-notch impact:	
Room temperature	95 ft-lb
0 F	50 ft-lb
−20 F	40 ft-lb
−50 F	25 ft-lb

Weld-Metal Composition

Carbon	0.08%	Phosphorus	0.008%
Manganese	0.85	Nickel	0.65
Silicon	0.45	Aluminum	0.04
Sulfur	0.012	Titanium	0.12

Table 29. Mechanical and Chemical Properties of Weld Metal From Type 4 (Fluorspar-Lime) Self-Shielding Flux-Cored Electrodes

Mechanical Properties of Weld Metal	
Tensile strength	89,000 psi
Yield strength	77,000 psi
Elongation in 2 in.	25%
Reduction in area	53%
Charpy V-notch impact:	
Room temperature	63 ft-lb
0 F	27 ft-lb
−60 F	16 ft-lb

Weld-Metal Composition

Carbon	0.06%	Sulfur	0.012%
Manganese	1.56	Phosphorus	0.008
Silicon	0.49		

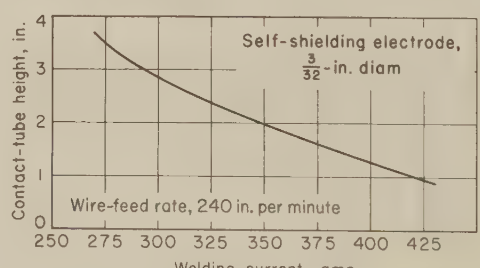


Fig. 25. Relationship between contact-tube height and welding current at a constant wire-feed rate for a typical self-shielding flux-cored electrode

Type 3 — Fluorspar-Lime-Titania. This type of self-shielding electrode is characterized by a heavy, dense slag with a golden color on the underside. The appearance of the slag is much like that of the slag from E7018 electrodes for shielded metal-arc welding, except that the slag from the E7018 electrode does not have the golden color on the underside.

Type 3 flux-cored electrodes give the best mechanical properties of all four types when used with self-shielding. If auxiliary carbon dioxide shielding is used, type 4 excels in notch toughness. A horizontal fillet weld from a type 3 electrode is more convex and exhibits a little more rollover on the lower leg than similar welds from types 1 and 2 electrodes, but has an excellent bead appearance in the flat position. The deposition rate is usually the highest of all four types. This type is excellent for welding high-carbon, high-sulfur, and other difficult-to-weld steels, because of its low penetration and excellent weld-metal quality. Because of the low carbon content of the weld metal and the low-hydrogen slag, the fluorspar-lime-titania flux is excellent for alloying the weld metal for steels of high tensile strength. Thus, it should find wide use in the repair welding of steel castings. It is not satisfactory for high travel speed on light frame stock, because the weld metal does not follow fast enough.

Typical mechanical and chemical properties of weld metal obtained from type 3 electrodes are given in Table 28.

Applications for type 3 self-shielding electrodes have few limitations in mechanical properties. If high penetration is desired, to get down into the root of a heavy weld, a short stickout and auxiliary carbon dioxide shielding can be used; then the joint is filled, using long stickout (2 1/2 to 3 in.) and a self-shielding electrode. Nozzles are available that can be adapted to either of these requirements.

Type 3 electrodes are ideally suited for high-carbon and other difficult-to-weld steels. Like type 1, they can be used for welding machinery and machinery parts, structural fabrications, field erections, column splices, beam-to-column connections, repair of heavy machinery, and repair of castings made of either carbon or alloy steel.

Type 3 is not intended for out-of-position welding. When drawn in 1/16-in. and smaller diameters, however, it can be used on straight polarity with low voltage (18 to 23 volts) and low amperage for out-of-position work. Normal application of the 3/32-in. and larger sizes of electrode requires a constant-voltage reverse-polarity type of power supply.

Type 4 — Fluorspar-Lime. This type of self-shielding electrode is characterized by a thin, light-brown slag. Its

flux and weld metal are similar to those of the lime-type electrode designed for use with auxiliary carbon dioxide shielding, but the weld metal is more likely to roll over at the lower leg of a horizontal fillet weld, and the surface is more convex. The fillet shape resembles that made with E7018 electrodes in shielded metal-arc welding. The bead appearance is not quite as smooth, and weld spatter is somewhat greater than for any of the other types of self-shielding electrodes. The multiple-pass weld metal shows a fairly high tensile strength, with fair elongation and reduction in area. Notch toughness is good, but x-ray soundness may be unsatisfactory. None of the brands tested met the x-ray standards of AWS A5.18-65T; they did meet grade II of AWS A5.1-64T. Typical properties are given in Table 29.

This type of flux-cored wire makes a versatile electrode that can be used with or without carbon dioxide shielding and is excellent for difficult-to-weld steels. When carbon dioxide shielding is used, the weld quality exceeds that of any other flux-cored electrode. This type of electrode can also be used successfully for welding frame steel at high speed with a short stickout (¾ to 1 in.). When this electrode is used as a self-shielding type, weld-metal transfer is globular and can easily trap slag. Moreover, the weld metal can contain considerable porosity that does not show on the surface of the metal if the voltage used is too high for the welding current or the electrode-feed rate.

Applications of type 4 as a self-shielding electrode are limited, particularly when x-ray quality is required. Likewise, type 4 yields the poorest-shape fillet of the four types. However, its high notch toughness makes it a good choice for low-temperature applications. When alloyed, its x-ray quality improves. Thus, for the repair of medium-carbon alloy steel castings such as 4140 and 4340, it can be used successfully. It is intended for both heavy and light weldments, similar to the applications listed for types 1 and 3. Like type 3, it is versatile, and when used with carbon dioxide shielding for deep root penetration, it gives the highest-quality weld of all types, including other carbon-dioxide-shielded types. Its inferior x-ray quality, however, restricts its application in comparison with type 3.

A comparison of the deposition rates of 3⁄32-in.-diam self-shielding electrodes of the four types is given in Fig. 24.

Figure 25 shows the relationship between contact-tube height (stickout) and amperage at a constant electrode-feed rate of 240 in. per minute for a typical 3⁄32-in.-diam self-shielding flux-cored electrode. Figure 26 gives relationships between amperage and wire-feed rate. Figure 27 compares deposition rates of covered electrodes for shielded metal-arc welding with auxiliary-gas-shielded and self-shielding flux-cored electrodes.

[Source article has illustrations of fillet welds in T-joints, and of horizontal welds in butt joints, made with auxiliary carbon dioxide shielding and with self-shielding electrodes.]

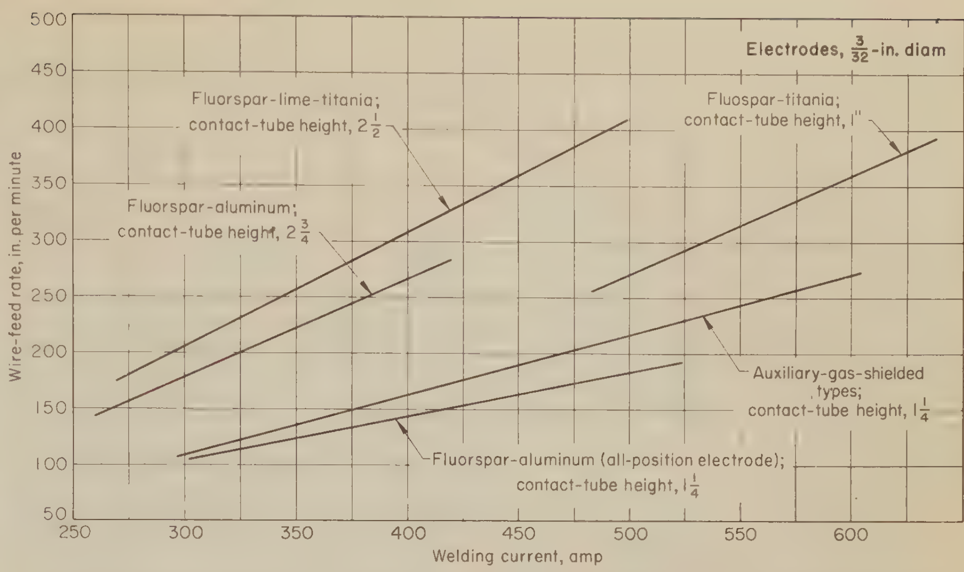


Fig. 26. Relationship between welding current and wire-feed rate for various types of self-shielding and auxiliary-gas-shielded flux-cored electrodes 3⁄32 in. in diameter

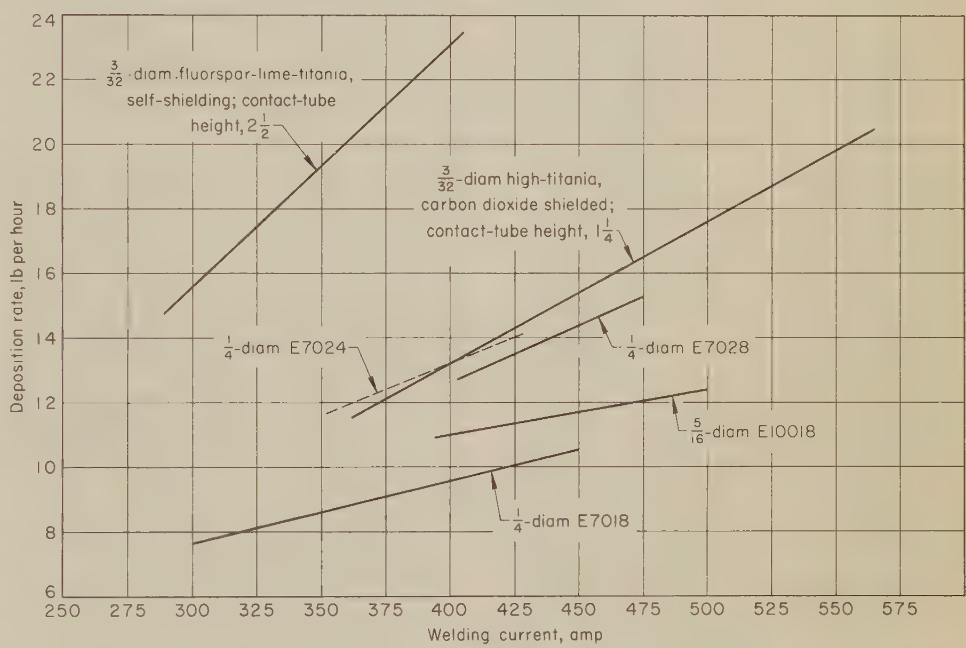


Fig. 27. Effect of welding current on deposition rate for four flux-covered electrodes (E7018, E7024, E7028 and E10018) and two flux-cored electrodes

Examples of Flux-Cored Arc Welding Presented Elsewhere in This Volume

Example	Subject of example
69	Comparison of times and costs for use of four different processes for welding a planetary-gear carrier made of low-carbon steel components
76	Comparison of welding conditions for three different processes used for joining components of a large bull gear made of 4140 and ASTM A36 steels
182	Butt welding 1045 steel plates 3⁄16 and ¼ in. thick, in production of an axle
183	Production of a gear by welding 1020 to 1045 steel in a T-joint with 3⁄32-in.-diam E70T-1 electrode wire, at 10 ipm, 600 amp and 32 volts, using CO_2 shielding gas
184	Edge welding 2-in.-thick ASTM A285 steel at 18 to 24 ipm, using 450 amp, 28 to 30 volts, and CO_2 shielding gas at 55 cu ft per hour
185	Joining 1050 and 1017 steel bearing-race components; root and filler passes in fillet and single-bevel-groove welds made with flux-cored alloy steel electrode wire
191	Flux-cored arc vs shielded metal-arc and gas metal-arc welding, for weld quality and cleanness of workpiece, in joining medium-carbon steel components
199	Shop and field joining of dragline-bucket components made of ASTM A514, type F, steel and alloy steel castings, by welding in flat and horizontal positions
200	Use of electrode wire of special composition to meet strength requirements for a 4130 steel weldment for a military vehicle
204	Welding conditions and costs for use of flux-cored arc vs shielded metal-arc welding for repairing an ASTM A217, grade WC9, alloy steel casting
212	Qualifying a procedure for welding ASTM A572, grade 50, to A36 steel in buildings
213	Joining forged 8620 steel to ASTM A36 steel, 3 and 5½ in. thick, with double-bevel-groove, single-J-groove and double-J-groove welds; 3⁄32-in.-diam electrode wire
366	Flux-cored arc vs electroslag welding for joining trunnion shoes made of ASTM A36 steel 2⅝ in. thick, using double-bevel corner joints

Submerged-Arc Welding

*By the ASM Committee on Submerged-Arc Welding of Steel**

SUBMERGED-ARC WELDING is an arc welding process in which the heat for welding is supplied by an arc (or arcs) developed between a bare-metal, consumable electrode (or electrodes) and a workpiece. The arc is shielded by a layer of granular and fusible flux, which blankets the molten weld metal and the base metal near the joint, and protects the molten weld metal from atmospheric contamination.

Principles of Operation

In submerged-arc welding, the electric current flows through the arc and the weld puddle, which consists of molten flux and molten weld metal. The molten flux is usually highly conductive, although cold flux does not conduct electricity. In addition to acting as a protective shield, the flux cover may supply deoxidizers and scavengers that react chemically with the weld metal. Fluxes for submerged-arc welding of alloy steel may also contain alloying ingredients that modify the composition of the weld metal.

Figure 1 shows how a submerged-arc weld is made. Electric current from a generator, transformer-rectifier, or transformer passes through the contact tube, and thence through the electrode wire, to produce an arc between the electrode and the base metal. The heat of the arc melts the electrode, flux, and some base metal, forming a weld puddle that fills the joint.

In all types of equipment, mechanically powered drive rolls continuously feed the bare-metal, consumable electrode wire through a contact tube (nozzle) and through the flux blanket to the joint being welded. The electrode wire, generally a low-carbon steel of closely controlled chemical composition, is coiled on a reel or in a drum. The electrode wire melts off at the weld zone and is deposited along the joint. Granular flux is deposited ahead of the arc, and, after the weld metal solidifies, unfused flux is removed by a vacuum pickup system, to be screened and reused. In automatic welding, flux recovery may be an integral function of the equipment, with a flux-recovery tube following directly behind the contact tube (see Fig. 2).

Submerged-arc welding is adaptable to both semiautomatic and fully automatic operation, although the latter, because of inherent advantages, is more widely used. In semiautomatic welding, the welder manually guides a welding gun (with flux hopper attached) that feeds the flux and the electrode to the joint, and he controls the rate of travel. In fully automatic welding, the equipment automatically feeds and guides the electrode and the flux along the joint and controls the rate of deposition. A typical machine for automatic submerged-arc welding is shown schematically in Fig. 2.

In some applications of automatic submerged-arc welding, two or more electrodes are fed simultaneously to the same joint. The electrodes can be side-by-side and fed into the same weld puddle, or they can be spaced just far enough apart to permit two weld puddles to solidify independently. The latter technique, sometimes referred to as tandem-arc welding, produces a multiple-pass weld in a single traverse of the joint, thereby increasing rate of deposition and welding speed.

Advantages and Limitations

Submerged-arc welding, either semiautomatic or fully automatic, offers the following advantages over some other welding processes:

1. Joints can be prepared with a shallow V-groove, resulting in less filler metal being used. (In some applications, no groove is required in joints between plates 1¼ in. or less thick.)
2. Shielding is not required to protect the operator from the arc, although eye protection is recommended. The arc operates under the flux cover, thus eliminating weld spatter.
3. The process can be used at high welding speeds and deposition rates to weld cylindrical or flat plate, or pipe, of virtually any size or thickness, and can be used for hard facing.
4. The flux acts as a scavenger and deoxidizer to remove undesirable contaminants from the weld puddle and to produce sound welds with good mechanical properties. The flux may, if required, supply alloying elements to the weld metal.
5. For welding unalloyed low-carbon steels, inexpensive electrode wires can be used — usually carbon steel wire, either bare or flash plated with copper, the latter to improve electrical contact and protect against rusting.
6. The submerged-arc process can be used for welding in exposed areas with relatively high winds; the granular flux shielding provides protection superior to that obtained from the electrode covering in shielded metal-arc welding.

Limitations of submerged-arc welding, some of which are also applicable to other welding processes, include the following:

1. Flux, flux-handling equipment, and workholding fixtures are required. Many joints also require the use of backing plates, strips or rings.
2. Flux is subject to contamination that may cause weld porosity.
3. To obtain welds of good quality, the base metal must be homogeneous and essentially free of scale, rust, oil and other contaminants.
4. Slag (solidified residue from the fused flux) must be removed from the weld bead, and this is sometimes a difficult operation. In multiple-pass welding, slag must be removed after each pass, to avoid entrapment in the weld metal.
5. The process usually is not suitable for use on metal less than 3⁄16 in. thick, because burn-through is likely.
6. Except for special applications, welding is largely restricted to the flat position for groove welds, and to the flat and horizontal positions for fillet welds, to avoid runoff of flux.

Suitable Work Metals

Submerged-arc welding is not adaptable to all metals and alloys. For convenience, metals and alloys may be divided into three groups with respect to their suitability to the process: most suitable, less suitable, and unsuitable.

Most Suitable Work Metals. Submerged-arc welding is used most widely in the production welding of unalloyed (plain) low-carbon steels containing not more than 0.30% carbon, nor more than 0.05% phosphorus and 0.05% sulfur. Most of the examples in this article deal with these steels, which range in tensile strength from about 45,000 to 85,000 psi and which usually are welded with a combination of flux and electrode wire included in AWS A5.17-69 (Specification for Bare Mild Steel Electrodes and Fluxes for Submerged-Arc Welding). Medium-carbon and low-alloy structural steels are equally well-

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W. R. Romance, General Manager, Manufacturing Operations, Harnischfeger Corp.; Edwin L. Rowe, Superintendent of Hull Fabrication, Foundry and Mill Machinery Group, Blaw-Knox Co.; William B. Sharav, Manager of Technology, Linde Div., Union Carbide Corp.; Emmett A. Smith (retired), formerly Chief Engineer, Electrode Div., Lincoln Electric Co.; Wade Troyer, Hobart Brothers Technical Center, Hobart Brothers Co.

Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees. A total of 24 examples of applications of submerged-arc welding appear in other articles in this volume, as recorded and briefly described in the table at the end of the Appendix to the present article, on page 77.

suited to submerged-arc welding, although they more often require preheating, postheating, and special electrode wires and fluxes.

Stainless steel, hardenable carbon steel, hardenable high-strength low-alloy steel, and hardenable high-strength structural steel are also welded by the submerged-arc process. Procedures for welding these steels are described in articles in this volume that deal individually with the welding of hardenable carbon steels, alloy steels, and stainless steels.

Submerged-arc welding is also used to deposit buildup and abrasion-resistant coatings on steel surfaces that are subjected to wear (see the article on Hard Facing by Arc Welding, which begins on page 152).

Less Suitable Work Metals. Some metals and alloys that can be submerged-arc welded are more often welded by processes that give a narrower heated zone. Some low-carbon, high-strength structural steels are included in this group, because of special notch-toughness and strength requirements that are difficult to meet by submerged-arc welding. Included also are high-carbon steels, maraging steels, and copper and copper alloys.

Unsuitable Work Metals. Cast iron usually cannot be submerged-arc welded, because it cannot withstand the thermal stress resulting from high heat input. However, Example 241 in the article on Arc Welding of Cast Irons describes an application in which malleable iron was submerged-arc welded to low-carbon steel. Problems are encountered with austenitic manganese steel and high-carbon tool steel, which are difficult to weld by any conventional welding process.

Aluminum alloys and magnesium alloys cannot be submerged-arc welded, because suitable fluxes are not available. Lead and zinc are unsuitable because of their low melting points. Titanium has been submerged-arc welded on an experimental basis, but no satisfactory flux for production welding has so far been developed.

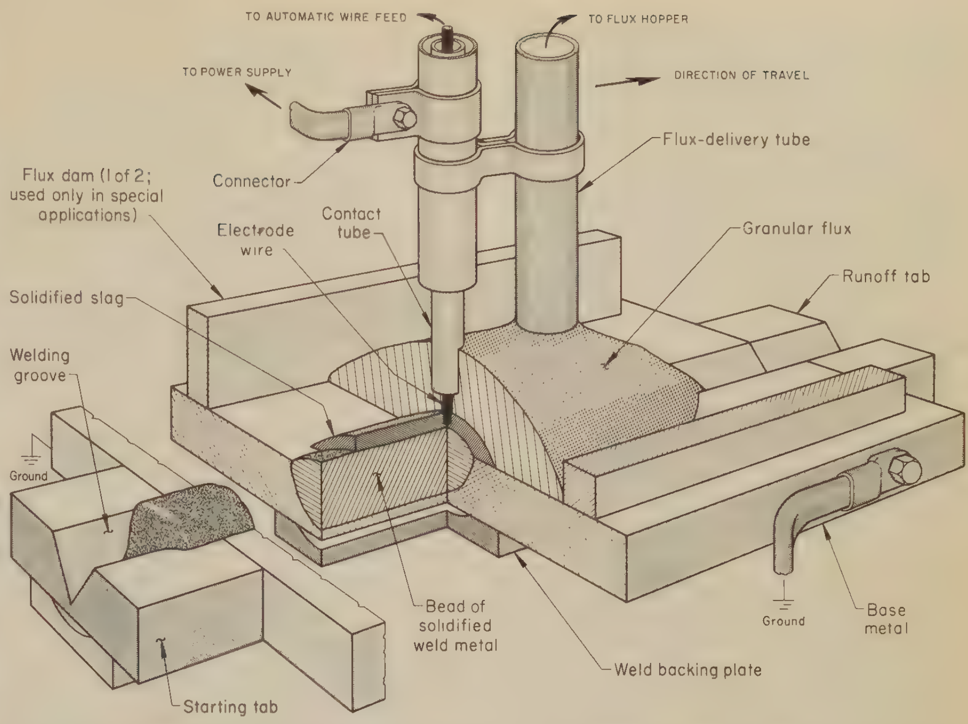


Fig. 1. Cutaway view of a single-V-groove weld in a butt joint, showing elements of an automatic submerged-arc welding operation

Metallurgical Considerations

Three characteristics of submerged-arc welding at high currents require special consideration: (*a*) the high percentage of base metal in the weld deposit when reverse-polarity direct current is used; (*b*) the large amount of slag that results from the operation; and (*c*) the large heat input, which affects microstructure.

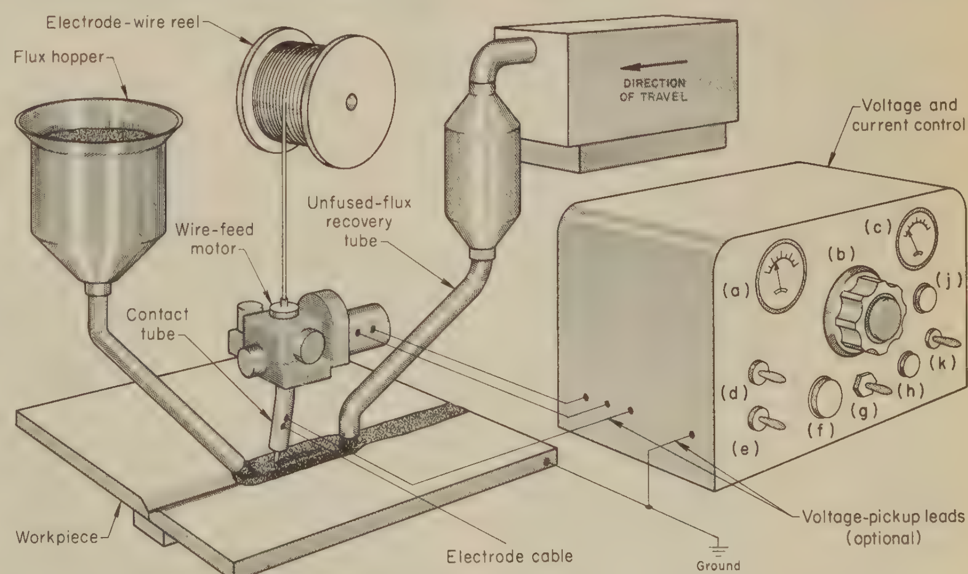
When the percentage of base metal in the weld deposit is high, it is important that harmful impurities in the base metal, such as sulfur and phosphorus, be held to a minimum.

The large amount of slag generally constitutes a source of silicon or manganese, some of which may be transferred to the weld deposit. Consequently, a low-silicon electrode wire (one containing 0.05% Si max) is generally used with high-silica fluxes, to prevent the weld metal from picking up excessive silicon. A low-manganese electrode wire, containing 0.50% manganese or less, is generally used with high-manganese fluxes. A high-manganese electrode wire, containing 2% manganese, is generally used with fluxes that contain little or no manganese (see the section "Effect of Flux Composition on Weld-Metal Composition", on page 74 in the Appendix to this article).

The large heat input that results from welding at high current (such as 1500 amp) at low travel speeds may coarsen the structure of the heat-affected zone and decrease its notch-toughness (raise its impact transition temperature).

Microstructural Changes. The extent of change in the structure of the base metal depends on four factors: the maximum temperature to which the metal is subjected, the time at that temperature, the chemical composition of the base metal, and the cooling rate.

The microstructure of the weld metal is columnar, because the grains start to form at the solid boundary and can grow in one direction only. In a hardenable carbon steel, the base-metal zone immediately adjacent to the weld metal may be coarse grained, because temperatures in the range of 2800 to 2200 F have been reached. Metal that has been heated to 2200 to 1700 F has a band of finer grain. Although this zone has been heated above the transformation range, the maximum temperature and the time at temperature have not been sufficient to cause grain coarsening. The next zone, 1700 to 1400



(a) Ammeter
(b) Welding-voltage adjustment
(c) Voltmeter
(d) Current adjustment
(e) Travel control
(f) Inch button
(g) Retract feed
(h) Weld stop
(j) Start
(k) Contactor

Fig. 2. Essential components of a typical machine for automatic submerged-arc welding

F, is one in which the steel has been annealed and is considerably softer than in the adjoining zones. From here out to the unchanged base metal, there may be carbide spheroidization, due to prolonged holding near 1330 F.

Preheating and Postheating. The principles of preheating and postheating are the same for submerged-arc welding as for other arc welding processes. Preheating and postheating are applied to hardenable steels, particularly steels whose carbon content exceeds about 0.30%, in thicknesses greater than ¾ in.

The reduction in cooling rate that results from preheating increases the time during which the heat-affected zone is in the temperature range above the start of martensite formation, and therefore promotes transformation of austenite to a softer pearlite instead of to hard martensite. A preheated weld is less likely to have hard zones than a weld that was not preheated. Also, because of the low cooling rate associated with preheated steel, thermal stresses are lower, decreasing the risk of weld cracking.

Postheating is used when needed to provide stress relieving, annealing, normalizing or tempering.

Power Supplies

Power supplies for submerged-arc welding are: (*a*) motor-generators and transformer-rectifiers, for direct-current (dc) output; (*b*) transformers, for alternating-current (ac) output. Either alternating current or direct current produces acceptable results in submerged-arc welding, although each has distinct advantages in specific applications — depending on the amperage range, diameter of the electrode wire, and travel speed — as outlined in the following list:

1. Semiautomatic welding done with electrode wire 5/64 or 3/32 in. in diameter, at input current of 300 to 550 amp: use of direct current predominates.
2. Automatic welding with a single electrode at low current (300 to 500 amp) and high travel speed (40 to 200 ipm): use of direct current predominates.
3. Automatic welding, single electrode, medium current (600 to 900 amp), travel speed of 15 to 30 ipm: either alternating or direct current is used.
4. Automatic welding, single electrode, high current (1200 to 2500 amp), travel speed of 5 to 15 ipm: use of alternating current predominates.
5. Automatic welding with two or more electrodes in the tandem position at 500 to 1000 amp per electrode; alternating current on all electrodes (or direct current on the lead electrode) is used.
6. Automatic welding with two electrodes in the transverse position: either alternating or direct current is used.

Direct Current. The characteristics of the power supply for submerged-arc welding with direct current are essentially continuous current and continuous voltage, uninterrupted by short circuits, as shown in the superimposed oscillograms in Fig. 3(a). At the start of welding there is a surge of current as the arc is initiated. The current should drop to the desired value within a small fraction of a second.

Direct current may be supplied by a motor-generator or a transformer-rectifier. A motor-generator consists of an alternating-current motor connected by a common shaft to a direct-current generator; the generator field may be separately excited or self-excited. A transformer-rectifier is a transformer with selenium or silicon rectifiers to convert alternating current from the main power line to direct current. As they relate to submerged-arc welding, the important features of generators and transformer-rectifiers are the rated and maximum current outputs (see Table 1) and the volt-ampere characteristic curves.

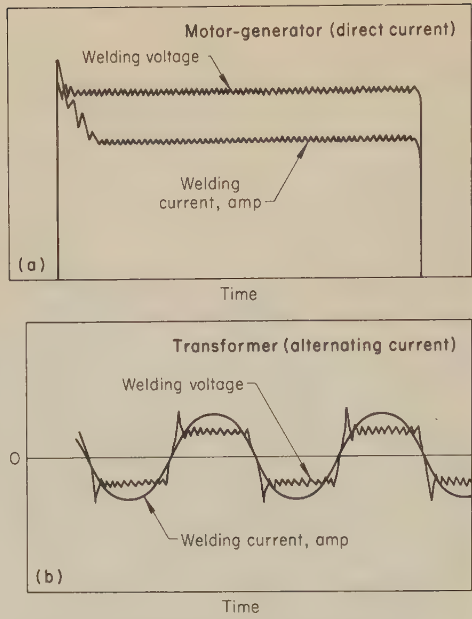


Fig. 3. Oscillograms (superimposed) for welding current and voltage for a motor-generator and a transformer

Volt-ampere characteristic curves are curves that show the voltage at which every value of current is provided under steady conditions. The curves are obtained by loading the welding machine with variable resistance and plotting the voltage at the electrode and work terminals for each ampere output.

Table 1. Output Ratings of Power Supplies Used in Submerged-Arc Welding

Volt-ampere characteristic	Rated amperage	Rated voltage	Duty cycle
Motor-Generators			
Drooping dc ..... (constant current)	300	32	60 (a)
	400	36	60 (a)
	500	40	60 (a)
	600	44	60 (a)
Flat dc .... (constant voltage)	300	25	100 (b)
	500	40	100 (b)
	750	40	100 (b)
	900	40	100 (b)
Transformer-Rectifiers			
Drooping dc ..... (constant current)	400	36	60 (a)
	500	40	60 (a)
	600	44	60 (a)
	800	44	60 (a)
Flat dc .... (constant voltage)	300	30	100 (b)
	500	37	100 (b)
	750	50	100 (b)
	1000	55	100 (b)
Transformers			
Drooping ac ..... (constant current)	400	36	60 (a)
	500	40	60 (a)
	600	44	60 (a)
	750	44	75 (c)
	1000	44	75 (c)
	1500	44	75 (c)

(a) Rated current can be delivered continuously for 6 min out of every 10 min. (b) Rated current can be delivered continuously as long as required. (c) Rated current can be delivered continuously for 1 hr, and then for 45 min out of every hour for the next 3 hr.

In terms of equipment, two types of characteristic curves are available for submerged-arc welding — drooping and flat; these are illustrated by curves D and F, respectively, in Fig. 4. Curve D is called a drooping-characteristic curve because the voltage at the terminals of the motor-generator or transformer-rectifier decreases sharply as the current is increased. It is associated with a constant-current power supply providing either direct or alternating current. Curve F is called a flat-characteristic curve because the voltage remains almost constant as the current is increased. This curve is associated with a constant-voltage power supply providing direct current only.

The difference in welding action between flat-characteristic and drooping-characteristic motor-generators or transformer-rectifiers is shown by plotting the volt-ampere characteristics of two submerged welding arcs (arcs 1 and 2) on the same graph with curves D and F (see Fig. 4). Arc 2 has higher voltage than arc 1, and therefore is a longer arc. It is assumed that the electrode wire is advancing at constant speed. If, because of a sudden change in level of the workpiece, the arc voltage increases from that of arc 1 to that of arc 2, the current will shift to a slightly lower value on the drooping-characteristic power supply, but on the flat-characteristic supply, there is a larger decrease in current. The flat-characteristic power supply will return the arc to arc 1 voltage more rapidly than will the drooping-characteristic supply. Thus, a motor-generator or transformer-rectifier with flat characteristic has an advantage when used with a constant-speed wire-feeding system of control. This system is applicable to welding with small-diameter wire, such as 1/16 in., which is fed at rates that make the current response of the flat characteristic almost instantaneous. With larger-diameter wire (5/32 in. and over), the wire feed is so slow that the fast current response of the flat characteristic is of little or no consequence. The drooping-characteristic power supply with a voltage-controlled wire feeder then becomes more advantageous.

Alternating Current. The power demand for submerged-arc welding with alternating current from a transformer approximates a sine wave of amperage and a rectangular wave of voltage (see Fig. 3b). There is a reversal of polarity at every half-cycle with an associated peak voltage to reignite the arc. The power is supplied by a transformer with a drooping characteristic — that is, a constant-current transformer. Alternators have never been used for submerged-arc welding. Table 1 shows rated amperage for transformers at various duty cycles.

Most transformers are provided with reactance, to stabilize the arc. High-current-capacity transformers for submerged-arc welding have an open-circuit voltage of 80 to 100 volts to accommodate the high arc voltage needed to start and stabilize the ac arc. For transformers with lower current capacities, the open-circuit voltage usually is 65 to 75 volts. Transformers with open-circuit voltage of less than 65 volts are not suitable for submerged-arc welding. There are several satisfactory systems for changing the transformer setting; one of these, the saturable-reactor control, is most convenient for remote control.

As previously noted, alternating current is preferred in both automatic welding with a single electrode at a

high current level and in automatic, multiple-electrode tandem-arc welding. For high-current applications, transformers are more economical than motor-generators. Furthermore, the high current facilitates arc starting, and alternating current reduces the severe arc blow encountered with direct current at high amperage. For lower-current applications, direct current is better than alternating current for sharp-wire and scratch starts. At high travel speed, constant-voltage direct current provides more-uniform weld beads than does alternating current.

Wire-Feeding Systems

Equipment for feeding the electrode wire in submerged-arc welding employs either of two types of system for control of wire-feed rate — voltage-sensitive systems and constant-speed systems. Voltage-sensitive control systems are used with constant-current power supplies, whereas constant-speed control systems are used with constant-voltage power supplies.

Voltage-sensitive systems are those in which the power supply maintains an essentially constant welding current, and the electrode feeder varies the feed rate of the electrode wire to maintain a constant arc voltage. This is accomplished by monitoring the arc voltage and having the voltage control momentarily increase the wire-feed rate when the voltage increases beyond a preset level, or decrease the feed rate when the voltage drops. A voltage-sensitive control system is preferred for high-current welding, particularly when the current density is more than 35,000 amp per square inch of the cross-sectional area of the electrode wire.

Constant-speed systems are essentially the same as voltage-sensitive systems, except for the substitution of a constant-speed control for the voltage control. In a constant-speed system, the arc voltage is preselected at the power supply, which is designed to maintain this preselected voltage irrespective of the current demand. (This system is also known as a constant-potential system.) The wire is fed at a predetermined rate, and arc length is held constant through automatic adjustment of the current by the power supply to maintain fixed resistance across the arc. Compared with a voltage-sensitive control system, a constant-speed control system provides increased voltage stability, consistent scratch starting, and more convenient adjustment of voltage and current. Constant-speed systems are particularly suitable for the high-speed welding of thin metal. Best results are obtained when the current density is in excess of 35,000 amp per square inch of the cross-sectional area of the electrode wire.

Electrode Wire

Electrode wire for submerged-arc welding of steel is available commercially in sizes from 0.045 to ⅜ in. in diameter (although the 0.045-in.-diam wire is not listed in AWS specification A5.17-69). Electrode wire ⅜ in. in diameter is seldom used. The electrodes are produced in various ferrous alloy compositions, ranging from unalloyed low-carbon steel to special high-alloy steel.

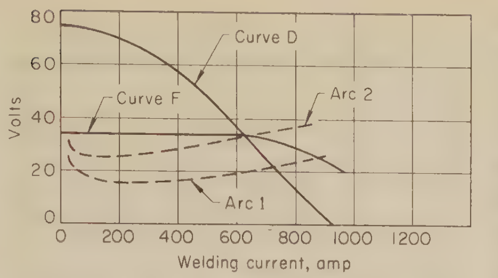
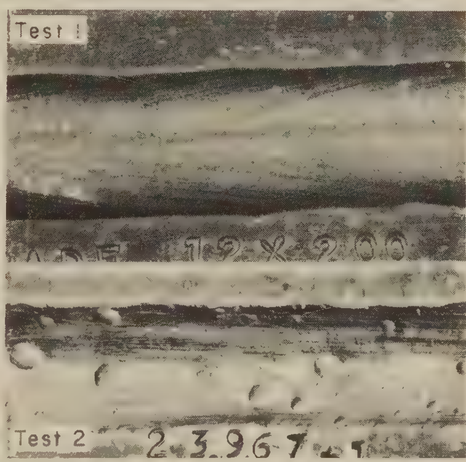


Fig. 4. Static volt-ampere curves of motor-generators or transformer-rectifiers with drooping (curve D) and flat (curve F) characteristics. See text for a discussion of the relation of curves D and F to curves for arcs 1 and 2.

Packaging. The continuous unalloyed low-carbon steel electrode wire is either coiled, or wound into drums. (Straight lengths of wire can be used for laboratory work, but are rarely used commercially.) The weights of electrode coils vary slightly from manufacturer to manufacturer. Typically, electrode wire ⅛ in. in diameter or smaller is available in coils weighing 25 or 60 lb. Electrode wire $\frac{5}{32}$ in. in diameter or larger is available in coils weighing 150 or 200 lb. The weight tolerance for all coils is ±10%. The smaller coils are used where weight reduction and compactness are essential — as in semiautomatic welding.



Item	Test 1	Test 2
Mechanical Properties of Weld Metal		
Yield strength, psi	65,000	58,000
Tensile strength, psi	85,000	77,000
Elongation in 2 in., %	28	26
Reduction in area, %	56	59
Charpy impact, ft-lb:		
Room temperature	25	50
−20 C (−4 F)	10	18

Welding Conditions for Both Tests

Base metal	ASTM A515, gr 70, steel, ½ in. thick
Joint type	Butt
Weld type	Single-V-groove; copper backing
Joint preparation	Machined
Flux	F61
Electrode-wire diameter	$\frac{5}{32}$ in.
Welding position	Flat
Power supply	1200-amp transformer
Current	500 amp
Voltage	30 v
Welding speed	30 ipm
Number of passes	One
Preheat and postheat	None

The test 2 weld bead, made with electrode wire containing 0.50% manganese, is deeply cratered, contrasting with the smooth, sound weld bead made in test 1 with electrode wire containing 2% manganese.

Fig. 5. Two weld beads made by submerged-arc welding under similar conditions but using electrode wires of different compositions (Example 47)

Table 2. AWS Classifications and Composition Limits for Electrodes for Submerged-Arc Welding (AWS A5.17-69)

AWS classification	Composition, %(a) C	Mn	Si
Carbon Steel (Low Manganese) Electrodes			
EL8	0.10 max	0.30-0.55	0.05 max
EL8K	0.10 max	0.30-0.55	0.10-0.20
EL12	0.07-0.15	0.35-0.60	0.05 max
Carbon Steel (Medium Manganese) Electrodes			
EM5K(b)	0.06 max	0.90-1.40	0.40-0.70
EM12	0.07-0.15	0.85-1.25	0.05 max
EM12K	0.07-0.15	0.85-1.25	0.15-0.35
EM13K	0.07-0.19	0.90-1.40	0.45-0.70
EM15K	0.12-0.20	0.85-1.25	0.15-0.35
2% Manganese Steel Electrode			
EH14	0.10-0.18	1.75-2.25	0.05 max

(a) Electrodes of all classes also contain maximums of 0.035 S, 0.03 P, 0.15 Cu (independent of coating), 0.50 total other elements. (b) Also contains 0.05 to 0.15 Ti, 0.02 to 0.12 Zr, 0.05 to 0.15 Al — exclusive of the 0.50% content of "total other elements".

Drums of electrode wire are used primarily in high-production applications, where a large volume of wire is consumed and where the welding equipment has been designed to support and channel the electrode wire from the drum into the welding head. Electrode wire 0.045 to ¼ in. in diameter is available in drums weighing 250 to 300, 500, 700 to 750, and 1000 lb net.

Composition. The composition of steel electrode wire, including that used in welding low-carbon steel, is a factor in the establishment and control of the composition of the weld metal. Other important factors are the composition of the flux and of the base metal, and the welding procedure.

Table 2 lists AWS classifications and composition limits for nine different types of electrode wires that are widely used for submerged-arc welding of low-carbon steels. These electrodes may be used in suitable combination with ten AWS classes of flux to produce weld metal with specified mechanical properties (see Table 5). Many carbon and alloy steel electrodes of compositions different from those shown in Table 2 are available. The compositions of six low-alloy steel electrodes commonly used in submerged-arc welding are given in Table 3.

As shown in Table 2, the standard steel electrode wires contain controlled amounts of carbon, manganese and silicon, with residual amounts of sulfur and phosphorus. When all other significant variables remain constant, appreciable variation in the amounts of these elements contained in the electrode wire may significantly affect weld quality, as demonstrated in the following example.

Example 47. Effect of Electrode Composition on Quality of Weld Bead (Fig. 5)

Variations in the quality of submerged-arc butt welds made in ½-in.-thick ASTM A515, grade 70, steel plate were attributed to differences in electrode-wire composition. Test joints were welded under identical conditions, including use of the same flux (composition of which was not identifiable) but using two different electrode wires of the following compositions:

Table 3. Compositions of Low-Alloy Steel Electrodes Commonly Used in Submerged-Arc Welding

Common designation	C	Mn	Si	P	S	Cr	Ni	Mo
	Composition, %(a)							
½ Mo	0.13	1.95	0.04	0.010	0.020	...	...	0.53
½ Mo – 1 Ni	0.14	1.85	0.04	0.010	0.015	...	1.00	0.51
1¼ Cr – ½ Mo	0.10	0.65	0.15	...	...	1.53	...	0.56
2¼ Cr – 1 Mo	0.10	0.62	0.20	...	...	2.47	...	0.95
4130	0.30	0.50	0.31	0.024	0.021	0.90	...	0.21
8620	0.21	0.78	0.32	0.020	0.023	0.50	0.60	0.22

(a) Although the compositions listed apply to electrode wire, similar compositions of deposited weld metal can be obtained when an unalloyed low-carbon steel electrode wire is used in conjunction with a suitable alloy-containing flux.

	C	Mn	Si	S	P
Test 1	0.14	2.00	0.03	0.024	0.017
Test 2	0.09	0.50	0.03	...	0.017

As shown in Fig. 5, weld beads made in test 1 were smooth and sound and would be expected to pass radiographic examination, whereas those made in test 2 had craters and ripples and probably would not pass radiographic examination even after dressing or grinding to remove the surface roughness. Results of mechanical testing of the weld metal deposited in the tests are shown in the table accompanying Fig. 5.

Analysis of the weld metal in the two beads showed:

Test 1 .... 0.14 C, 0.74 Mn, 0.25 Si
Test 2 .... 0.11 C, 0.50 Mn, 0.22 Si

Because manganese serves both as a deoxidizing agent and as a strengthening element, the cratered surface, irregular outline of the weld, and lower strength of the weld metal in test 2 were attributed to the lower manganese content. If this deficiency had been known in advance of welding, it might have been overcome by using a flux capable of adding an adequate amount of manganese to the weld metal.

Surface Condition. Most unalloyed, low-carbon steel electrode wire is lightly coated with copper during manufacture. The copper coating provides some protection from rust and ensures good electrical contact between the electrode and the contact tube (nozzle) of the welding head. Good electrical contact is essential to the maintenance of satisfactory arc characteristics.

Electrode wire should have a smooth, clean surface. Rust and other surface contaminants can produce weld porosity, cause excessive wear of contact tubes, and adversely affect arc characteristics. Some small-diameter electrode wire is coated with a small amount of a special hydrogen-free lubricant. This lubricant helps to feed the wire through the welding-cable conduit that carries the wire from the semiautomatic wire feeder to the welding-gun contact tip.

Table 4. Current Ranges for Electrode Wires Used in Submerged-Arc Welding

Wire diameter, in.	Current range, amp(a)	Wire diameter, in.	Current range, amp(a)
0.045	100 to 350	5⁄32	340 to 1100
1⁄16	115 to 500	3⁄16	400 to 1300
5⁄64	125 to 600	7⁄32	500 to 1400
3⁄32	150 to 700	¼	600 to 1600
⅛	220 to 1000	5⁄16	1000 to 2500
		⅜	1500 to 4000

(a) Upper and lower limits of ranges are extremes and are rarely used.

Table 5. Mechanical-Property Requirements for Flux Classification (AWS A5.17-69) (a)

Tensile strength:
- Classes F60 thru F64 ...62,000 to 80,000 psi
- Classes F70 thru F74 ...72,000 to 95,000 psi

Yield strength (0.2% offset), min:
- Classes F60 thru F64 ....50,000 psi
- Classes F70 thru F74 ....60,000 psi

Elongation in 2 in., min (all classes) ..22%(b)

Charpy V-notch impact strength:
- Classes F60 and F70 ....Not required
- Classes F61 and F71 ....20 ft-lb at 0 F
- Classes F62 and F72 .....20 ft-lb at −20 F
- Classes F63 and F73 .....20 ft-lb at −40 F
- Classes F64 and F74 .....20 ft-lb at −60 F

(a) Mechanical properties are those of the weld metal, produced by one of the classes of flux in combination with an electrode of one of the classes shown in Table 2. A flux designation consists of the class number, as shown in the present table, followed by the designation of the electrode used in combination with it (for example, F60-EL8). (b) For each increase of one percentage point, the tensile strength or the yield strength, or both, may decrease 1000 psi to minimums as follows: tensile strength, 60,000 psi (F60 through F64) and 70,000 psi (F70 through F74); yield strength, 48,000 psi (F60 through F64) and 58,000 psi (F70 through F74).

Table 6. Conditions and Results of Tests To Determine Effect of Silicon Content of Flux on Silicon Content of Weld Metal (Example 48) (a)

Flux type, test 1 ....Special low-silicon
Flux consumption, test 1 .....0.15 lb per min
Flux type, test 2 ....General purpose(b)
Flux consumption, test 2 .....0.20 lb per min

Welding Conditions for Both Tests

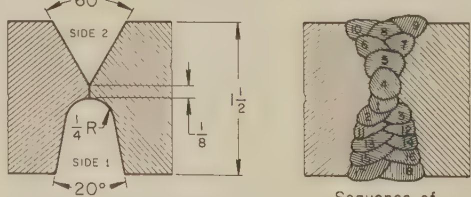
Joint type ....Butt
Weld type ....U-groove (side 1), V-groove (side 2)
Joint preparation ....Machining
Welding position ....Flat
Power supply ....40-v, 600-amp transformer-rectifier
Preheat and postheat ....None
Electrode ....3⁄32-in.-diam EH14
Electrode stickout ....1 in.
Deposition rate ..0.5 lb per min per 1000 amp
Number of passes 18
Sequence and conditions of the 18 passes:

Side	Pass No.	Current (dcrp), amp	Voltage	Travel speed, ipm
1	1	320	27	20
	2	320	28	18
	3	320	28	18
2	4	350	26	15
	5	330	28	8
	6	330	30	8
	7-10	320	30	8
1	11-18	320	30	8

Chemical Compositions

Base metal ..... 0.20 C, 0.60 Mn, 0.008 Si
Electrode ...... 0.14 C, 2.00 Mn, 0.024 Si
Weld metal, passes 6 and 7:
Test 1 .... 0.09 C, 1.00 Mn, 0.014 Si
Test 2 .... 0.09 C, 0.95 Mn, 0.400 Si

Low-carbon steel (ASTM A285, grade C); 2% Mn steel filler metal (EH14)



Joint detail before welding

Sequence of weld passes

(a) Test welds were made in butt joints as illustrated above, which were between plates of a pulp digester that required weld metal with a silicon content of less than 0.015% to ensure corrosion resistance. (b) Contained a significant amount of silicon dioxide (silica) and no ferrosilicon or other deoxidizer.

Selection of wire size (diameter) depends on equipment requirements and application. Small-diameter electrode wire (0.045 through 5⁄64 in.) is used almost exclusively with semiautomatic welding equipment. The 3⁄32-in.-diam electrode wire is used with either semiautomatic or fully automatic equipment. Larger sizes (⅛-in. diameter and above) are used only with fully automatic equipment, because their use with semiautomatic equipment would make the welding cable leading to the semiautomatic welding gun too stiff and difficult to handle.

Small-diameter electrode wires (0.045 through 5⁄64 in.) are more flexible and perform better at low currents than large-diameter wires of the same composition and type. Flexibility is essential to the use of semiautomatic submerged-arc welding equipment. If the electrode wire is too stiff, the welder will find the welding gun and cable too difficult to manipulate into positions necessary to produce sound welds. A stiff welding cable also increases welder fatigue, thereby reducing arc time and efficiency.

Most semiautomatic submerged-arc welding is done with electrode wire 5⁄64 or 3⁄32 in. in diameter. The use of wire less than 5⁄64 in. in diameter is usually limited to applications requiring stable arc characteristics at low current — for example, for joining thin metal, for making circumferential welds on small-diameter assemblies, and for multiple-arc welding. In addition to their ability to develop stable arc characteristics, small-diameter wires provide better control of the molten weld puddle and of bead size and shape, and provide a more uniform weld appearance.

Large-diameter electrode wires (5⁄32 to ⅜ in.) are used to take advantage of higher current capacity and increased deposition rate (see Example 49). They are occasionally used to reduce depth of penetration and to increase bead width. Also, the large sizes make tightness of fit-up at the root of a joint less critical.

For large-diameter wire, the components of the wire-feeding mechanism, including the drive rolls, gearbox, electric motor, and wire straightener, must be larger and more ruggedly constructed than for small-diameter wire. This is essential to ensure uniform operating characteristics and to maintain weld quality.

Current Range. In submerged-arc welding, an electrode of a specific diameter can operate within an unusually wide current range, as shown in Table 4. The overlap of current ranges makes it possible to use any of several wire sizes at a particular welding-current setting. Changing to a smaller-diameter electrode wire at a given current may serve to increase depth of fusion and reduce the width of the weld bead.

With small-diameter electrode wire, the arc is initiated more readily than with a wire of large diameter, and small-diameter wires are particularly well-suited to hot starts and to high-frequency arc starting. When the welding current is at the low side of one of the current ranges given in Table 4, an electrode wire of the next-smaller diameter (resulting in a higher current density) will provide a more stable arc and a higher deposition rate.

Fluxes

Fluxes used in submerged-arc welding are granular, fusible, mineral materials containing oxides of manganese, silicon, titanium, aluminum, calcium, zirconium, and magnesium, and other

compounds. They are melted by the welding arc and, in the molten condition, blanket the weld metal and shield it from atmospheric contamination. Fluxes are generally chemically neutral with respect to the weld metal, must not evolve large amounts of gases during welding, and must have electrically stable welding characteristics.

Fluxes are classified by AWS on the basis of the mechanical properties of a weld deposit made with a particular combination of flux and electrode (see Table 5). A flux used in combination with an electrode of any of the classes shown in Table 2 must produce weld metal that conforms with the requirements in Table 5.

Additional information on fluxes is given in the Appendix to this article, beginning on page 73.

Low-silicon fluxes are used in applications where the silicon content of the steel base metal and of the weld deposit must be low to prevent excessive corrosion. A typical application is the welding of pulp digesters, which are subject to corrosive attack by digester liquids. The example that follows compares the compositions of the weld metal produced in such an application when using a special low-silicon flux and when using a general-purpose flux.

Example 48. Use of Low-Silicon Flux in Welding Joints for Service in Corrosive Environment (Table 6)

The plates of a pulp-digester tank were butt welded together by submerged-arc welding in 18 passes as shown in Table 6. The plates were made of 1½-in.-thick ASTM A285, grade C, low-carbon steel. It was important that the silicon content of the metal exposed to the digester fluids be below about 0.015% to minimize corrosion.

To determine the effect of the silicon content of the flux on the silicon content of the weld metal, test plates were welded using a special low-silicon flux (test 1), and other test plates were welded under the same conditions but using a general-purpose flux containing a significant amount of silicon dioxide (silica) and no ferrosilicon or other deoxidizer (test 2).

The carbon, manganese and silicon contents of weld beads made with the two fluxes are compared in Table 6. The weld bead that was made with the special low-silicon flux (test 1) contained only 0.014% Si, in contrast to the 0.40% Si contained in the bead made with the general-purpose flux (test 2). Welding conditions for the two tests are given in Table 6.

Particle Size. Fluxes for submerged-arc welding are available in a variety of sizes ranging from 8×48 to 48×325 mesh. These flux-size numbers indicate the sizes of the largest and smallest particles present; for example 8 × 48 indicates that 90 to 95% of the particles will pass through a screen having eight openings per inch and only 2 to 5% will pass through a screen having 48 openings per inch.

Flux particle sizes, therefore, correspond to the meshes per lineal inch on a screen-scale sieve table, such as that given in Table 7. Particle sizes of 250 and smaller are sometimes referred to as "dust" and may be represented by the letter "D", rather than by a specific particle size number. Thus, some manufacturers use the designation 48 × D instead of 48 × 250, since the "D" designation may represent several particle sizes that are 250 mesh and smaller.

Table 7. Tyler Screen-Scale Sieves

Meshes per lineal, In.	Meshes per lineal, Cm	Sieve opening, In.	Sieve opening, Mm	Wire diameter, In.	Wire diameter, Mm
8	3.15	0.093	2.36	0.032	0.813
9	3.54	0.078	1.98	0.033	0.838
10	3.94	0.065	1.65	0.035	0.889
12	4.72	0.055	1.40	0.028	0.711
14	5.51	0.046	1.17	0.025	0.635
16	6.30	0.0390	0.991	0.0235	0.597
20	7.87	0.0328	0.833	0.0172	0.437
24	9.45	0.0276	0.701	0.0141	0.358
28	11.02	0.0232	0.589	0.0125	0.318
32	12.60	0.0195	0.495	0.0118	0.300
35	13.78	0.0164	0.417	0.0122	0.310
42	16.54	0.0138	0.351	0.0100	0.254
48	18.90	0.0116	0.295	0.0092	0.234
60	23.62	0.0097	0.246	0.0070	0.178
65	25.59	0.0082	0.208	0.0072	0.183
80	31.50	0.0069	0.175	0.0056	0.142
100	39.37	0.0058	0.147	0.0042	0.107
115	45.28	0.0049	0.124	0.0038	0.097
150	59.06	0.0041	0.104	0.0026	0.066
170	66.93	0.0035	0.089	0.0024	0.061
200	78.74	0.0029	0.074	0.0021	0.053
250	98.43	0.0024	0.061	0.0016	0.041
270	106.3	0.0021	0.053	0.0016	0.041
325	128.0	0.0017	0.043	0.0014	0.036

The choice of flux particle size for a particular welding application depends on the current to be used, type of flux, travel speed, and type of weld being made. Table 8 gives ranges of welding current for a number of standard flux sizes. Finer sizes are desirable for high welding currents, and are also used at lower currents, because they give wider and flatter weld surfaces. For welding over rust or oily surfaces, coarse sizes are preferred because they are more permeable and liberate gases more freely.

Particle Size vs Current. The particle size of the flux affects the amount of current that can be used in submerged-arc welding. In general, a higher welding current can be employed with a fine flux than with a coarse one, while maintaining a stable arc and producing sound, uniform welds. Too high a current for a given flux particle size causes arc instability and results in ragged and uneven weld edges and surfaces.

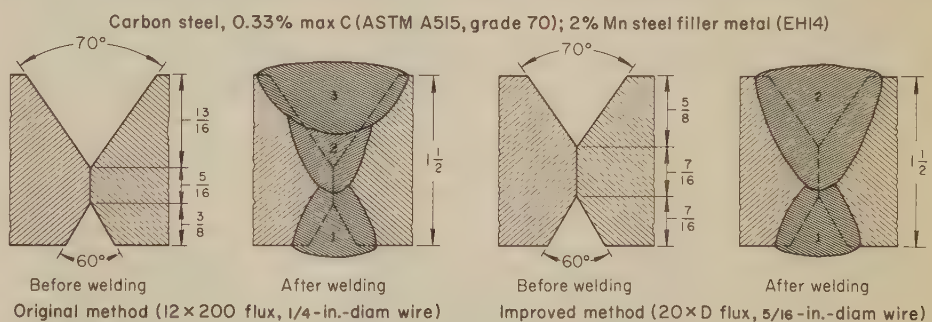
The higher current permissible and the more penetrating arc associated with a fine flux particle size and larger electrode-wire size may enable smaller grooves to be used in joining thick metal, with resultant savings, as in the application in the following example.

Example 49. Effect of Flux Particle Size and Electrode-Wire Size on Welding Current and Cost (Fig. 6)

The longitudinal seam in a 6-ft-diam by 24-ft-long unfired pressure vessel was originally butt welded in three passes, using size 12×200 flux. For full penetration in the 1½-in.-thick ASTM A515, grade 70, steel (0.33% max C), the joint design and double-V-groove weld were as shown at the left in Fig. 6.

Changing to a finer flux size (20 × D), and from a ¼-in. to a 5⁄16-in.-diam electrode wire, resulted in a substantial saving in labor and other costs by making it possible to complete the weld in two passes and reduce electrode and flux consumption. Because use of the finer flux particle size and larger electrode-wire size permitted welding at higher current, resulting in a more penetrating arc, total groove depth could be reduced by ⅛ in., with the same bevel angles, as shown at the right in Fig. 6.

Material and welding labor costs were reduced by 37% as a result of using 32% less filler metal, 20% less flux, and 46% less arc time. Other savings included less machining time for preparing the joint and a 29% reduction in the electrical power consumption for welding. Operating conditions and a detailed comparison of costs and cost factors for the original and the improved methods are given in the table



Welding Conditions for Both Methods

Joint type	Butt
Weld type	Double-V-groove
Joint preparation	Machining
Electrode stickout	1½ in.
Welding position	Flat
Deposition rate	0.5 lb per min per 1000 amp
Power supply	Transformer
Electrode class	EH14
Flux class	F72

Item	Original method	Improved method
Electrode diameter, in.	¼	5⁄16
Flux particle size	12×200	20×D
Cost per Foot of Weld		
Filler metal(a)	$0.503	$0.343
Flux(b)	0.332	0.264
Labor(c)	0.946	0.506
Total	$1.781	$1.113

Welding conditions	Original method, Pass 1	Original method, Pass 2	Original method, Pass 3	Original method, Total	Improved method, Pass 1	Improved method, Pass 2	Improved method, Total
Welding current (ac), amp	1050	1150	1250	...	1300	1600	...
Welding voltage	35	32	38	...	35	37	...
Travel speed, ipm	9	5	12	...	10	9	...
Flux consumption, lb per ft	0.86	1.65	0.81	3.32	1.10	1.54	2.64
Electrode consumption, lb per ft	0.75	1.46	0.66	2.87	0.83	1.13	1.96
Arc time, minutes	1.33	2.40	1.00	4.73	1.20	1.33	2.53
Power consumption, watt-hr(d)	814.6	1472	825	3111.6	910	1312	2222

(a) At $0.175 per pound. (b) At $0.10 per pound. (c) At $6 per hour; 50% arc time. (d) Net power consumption, neglecting efficiency and power factors.

Fig. 6. Reduction in groove depth of a longitudinal butt joint in a pressure vessel, and decrease in number of weld passes (which decreased welding cost), that were made possible by changing from a coarse flux to a small-particle-size flux and by using larger-diameter electrode wire (Example 49)

that accompanies Fig. 6. The major fraction of the cost saving was in labor charges.

To avoid excessive arc blow and to minimize power cost, alternating current was used. Arc initiation was by means of steel wool. Soundness of welds was checked by x-ray inspection. The welds were stress relieved at 1250 F for 4 hr.

Care of Fluxes. Commercial fluxes are thoroughly dry when shipped from the manufacturer, and are packaged in moisture-resistant containers to keep them dry. Fluxes should be stored in dry areas. If they become damp or wet, they can be dried by heating, usually at 750 F for about one hour. Moist or damp flux causes porosity and cracking in weld metal. Oil and rust contamination also cause porosity and should be avoided. When flux can be recycled after being used, care should be taken to avoid contamination with rust, mill scale, and other foreign substances.

Jigs, Fixtures and Booms

Because requirements vary with the shape, size and weight of individual workpieces, jigs and fixtures are subject to few firm rules of design and construction. However, the following design principles are generally applicable:

1. The fixture should serve to position the weld in the flat position.
2. Designs should be simple, to minimize cost.
3. Loose clamping should be avoided.
4. Fast-acting clamps (hand, air or hydraulic) are recommended.
5. Clamps should be adequately spaced from the joint being welded.
6. The ground connection, or connections, for the fixture should be located for most effective grounding and best control of arc blow.
7. The fixture should minimize or eliminate the need for tack welds in the weldment.

In addition to their primary function of holding and positioning the workpiece during welding, fixtures may also serve to control or minimize distortion due to thermal stress. Thus, fixtures should be rigid enough to ensure retention of alignment during welding. Although the movement of critical areas may be restricted, provision must be made for thermal expansion and contraction. Fixtures may be stationary or mobile in relation to the welding head.

Lathe fixturing is commonly used in welding plugs or caps to the ends of cylinders, and in joining cylindrical sections, because it combines a clamping action with centering and controlled rotation. A typical lathe fixture and setup for simultaneously welding two plugs to the ends of a cylinder is described in the following example.

Table 8. Recommended Current Ranges for Standard Sizes of Fluxes Used in Submerged-Arc Welding

Flux size(a)	Current range, amp
8×48, 14×48(b), 12×65, 10×150	Up to 1100
12×150	600 to 1100
12×200	600 to 1750
20×200, 35×200	600 to over 1750

(a) Size numbers indicate maximum and minimum particle sizes; for example, size 8×48 means most of the particles will pass through a screen with 8 openings per inch and almost none will pass through a screen with 48 openings per inch. Numbers are screen-scale sieve numbers given in Table 7 (see also ASTM E11). (b) Typical size for bonded flux.

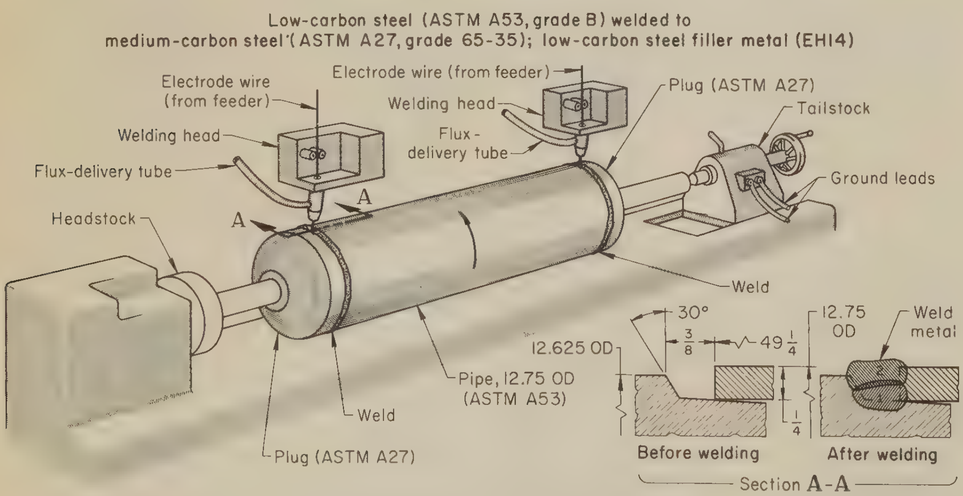
Example 50. Use of Lathe Fixturing in Welding Plug Ends of Cargo Cushions (Fig. 7)

Cargo cushions, used to control shock when coupling railroad freight cars, were assembled by welding a plug into each end of a 12.75-in.-OD pipe (¼-in. wall thickness), using automatic submerged-arc welding and the lathe setup shown in Fig. 7. The pipe, 49¼ in. long, was made of ASTM A53, grade B, steel. The beveled end plugs were cast from ASTM A27, grade 65-35, steel, and were tack welded into place before being submerged-arc welded to the tube. The welded joints had to withstand a hydrostatic test pressure of 430 psi.

The two plugs were welded simultaneously, using two welding heads mounted on separate carriages. Welding conditions are given in the table with Fig. 7.

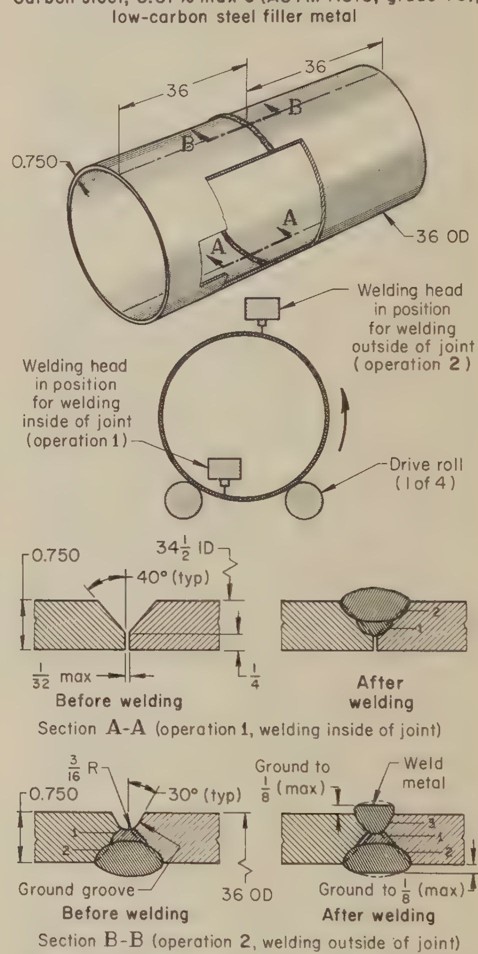
The assembly was supported and rotated in a rework lathe. Each weld was made in two passes, as shown in section A-A in Fig. 7. No postweld finishing was done. Sample welds were macroetch-inspected.

Use of Booms. Booms and extensions of various types are used to support and guide the welding head, to enable it to reach locations that are not readily accessible, such as the inside surfaces of tubes and cavities. A typical use of a boom in the circumferential welding of internal and external surfaces of cylinders is described in Example 51, which follows. (See also Example 61,



Process	Automatic submerged-arc welding
Joint type	Butt
Joint preparation	Machining
Weld type	Single-bevel-groove
Electrodes (two)	3/32-in.-diam EH14
Flux	F70; size 12×65
Electrode stickout	¾ in.
Welding position	Flat (horizontal-rolled pipe position)
Welding voltage	29 v
Welding current	350 amp, ac
Welding speed	14 ipm
Flux consumption per assembly	4.1 lb
Electrode consumption per assembly	2.88 lb
Number of passes per weld	Two
Power supplies	Two 48-v, 500-amp transformers
Preheat and postheat	None
Auxiliary equipment	Rework lathe
Production rate	Six assemblies per hour

Fig. 7. Use of a lathe fixture for support and rotation during simultaneous welding of two plugs to the ends of a pipe, in the production of a cargo cushion (Example 50)



Joint type	Butt
Weld type	Double-V-groove (back gouged)
Electrode wire	5/64-in.-diam low-carbon steel, copper-coated
Power supply	900-amp motor-generator(a)
Welding position	Flat(b)
Postheat	1650 F, 1 hr

	Inside bead	Outside bead
Joint preparation	Machining	Grinding
Welding voltage	34	35
Welding current (dcrp), amp	450-500	500-550
Welding speed, ipm	10-12	15-17
Number of passes	Two	One(c)

(a) With steep arc-voltage characteristic. (b) Horizontal-rolled pipe position. (c) Additional passes were sometimes necessary, depending on the extent of grinding.

Fig. 8. Joining of two rotated cylinders by deposition of inside, then outside, circumferential weld beads, using a welding head that was supported and guided by a boom (Example 51)

which describes the use of booms in longitudinal welding of cylinders.)

Example 51. Circumferential Butt Welding of Cylinders, Using a Boom and Motor-Driven Rolls (Fig. 8)

Two ASTM A515, grade 70, steel cylinders, each 36 in. in diameter, 36 in. long, and with 0.750-in. wall thickness, were joined end-to-end by automatic submerged-arc welding in two operations, as shown in Fig. 8. During welding, the assembly was rotated on drive rolls, and the welding head and flux feeder were supported and guided by a boom.

The two ends to be joined were machined to form a groove along the inside of the joint, and were aligned and butted to a maximum root opening of 1/32 in., as shown in the "Before welding" view in section A-A in Fig. 8. The two cylinders were held together for welding either by tack welds or by a continuous weld bead, around the outside of the joint. (The continuous bead was used to provide backing for the first pass of the inside weld when fit-up was not tight enough to prevent drop-through.)

Then the assembly was loaded onto four motor-driven rolls, and the automatic welder was set up for the first operation — welding the inside of the circumferential joint in two passes (see section A-A in Fig. 8). The boom-supported welding head was located on the circumference at a position such that the weld deposit would solidify before it could run downhill (see Fig. 8).

After the inside of the joint had been welded, the groove on the outside of the joint was back gouged by grinding to sound weld metal (see "Before welding" view in section B-B in Fig. 8), to prepare for welding of the outside. The groove was liquid-penetrant or magnetic-particle inspected to ensure complete removal of unsound metal.

The weld on the outside of the joint was made in one or more passes — the number depending on the extent of grinding in making the groove. Again, the welding head was positioned so as to keep the weld metal from running off.

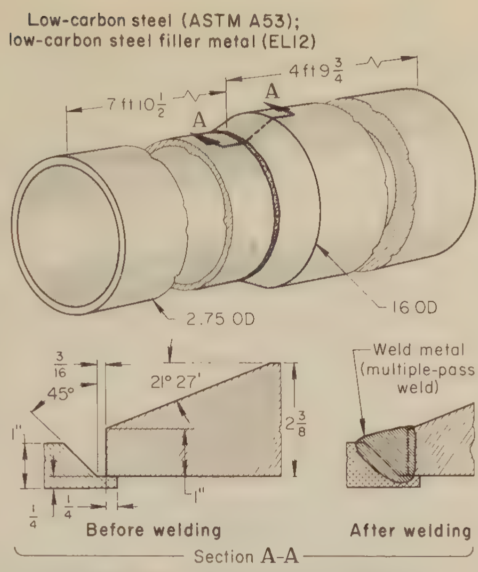
Both operations were done with the same welding head, with wire fed from the spool through the boom conduit to the welding head. Welding conditions are given in the table with Fig. 8. The welding was done with reverse-polarity direct current to obtain the desired control of bead shape and appearance, and consistent full penetration. All welds and welding procedures met requirements of the ASME Boiler and Pressure Vessel Code.

The completed weld was ground to within 1/8 in. above the cylinder surface on both sides. After 100% radiographic inspection, the cylinder weldment was given a postweld heat treatment at 1650 F for 1 hr.

Joint Design

Recommended designs of joints for use in submerged-arc welding are presented on pages 148 to 151 in this volume. These joint designs take into consideration the deep penetration that is characteristic of submerged-arc welding, and the difficulty of slag removal that attends deep-groove, multiple-pass welding. It will be noted that backing bars are used when needed to prevent burn-through and loss of flux. It is possible to obtain welds with 100% penetration in plates up to 5/8 in. thick without joint preparation, but a buildup of weld deposit will be produced on both surfaces. However, through the use of proper design that utilizes edges beveled by gas cutting, excessive reinforcement can be avoided.

Example 59 (and Fig. 25) in this article shows the effect of welding position on joint design.



Joint type	Butt
Weld type	Single-bevel-groove with integral backing
Electrode wire	1/8-in.-diam EL12
Flux	F71
Welding position	Flat (horizontal-rolled pipe position)
Welding voltage	28 v
Welding current	600 amp, dcrp
Travel speed	3 ipm
Preheat	250 F
Postheat	None
Number of passes	Six to eight
Production per 8-hr shift	Three assemblies

Fig. 9. Two pipes of different diameters joined by submerged-arc welding, with a land on the smaller pipe serving as a backing ring (Example 52)

Methods of Avoiding the Use of Backing Rings and Strips

The use of a solid backing ring or strip, to start a joint, or to obtain complete penetration while avoiding burn-through, can sometimes be avoided by redesigning the joint, or by the use of a flux bed as backing for the first pass (see Examples 57 and 61). This is desirable in applications that would require removal of the backing strip after welding is completed.

Joint Design. In the submerged-arc welding of pipes and other tubular workpieces, it is sometimes feasible to adopt a joint design that incorporates a backing lip, thereby eliminating the need for a backing ring or bar, which ordinarily would be required for preventing melt-through. Joint designs of this type are described in the following two examples.

Example 52. Incorporation of a Machine-Turned Land on Pipe To Serve as a Backing Ring (Fig. 9)

Sections of low-carbon steel pipes 12 3/4 and 16 in. in outside diameter, with wall thicknesses of 1 in. and 2 3/8 in., respectively, were joined as shown in Fig. 9. To facilitate and control fit-up of the two sections, the joint edges were machined so that the larger pipe would slip over a 1/4-in.-thick cylindrical land machined on the smaller pipe, as shown in section A-A in Fig. 9. In addition to aligning the pipe sections, the land served as a backing ring, and it completely contained the molten metal and flux.

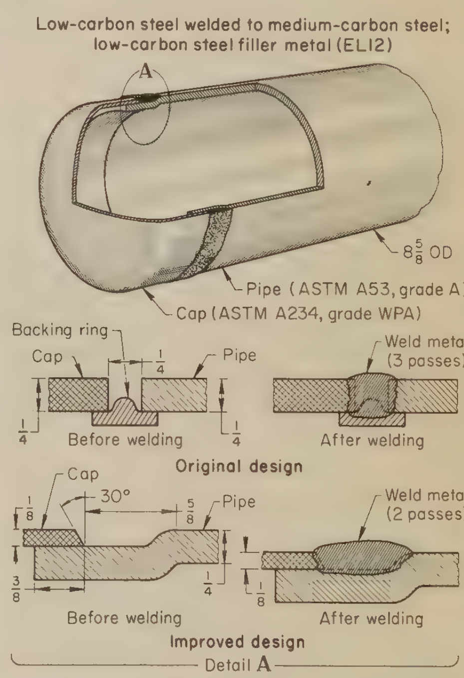
The joint was submerged-arc welded in six to eight passes with the pipe sections in the horizontal-rolled position, and with the welding head fixed in the 12 o'clock position. Welding conditions are given in the table that accompanies Fig. 9. The completed weld, after removal of flux, was inspected visually and by the magnetic-particle method.

Example 53. Use of an Offset in a Pipe To Eliminate Backing Rings (Fig. 10)

A component of a heat-exchanger shell assembly was initially made by submerged-arc welding a 1/4-in.-wall cap drawn from medium-carbon steel to a low-carbon steel pipe of the same wall thickness, by means of a circumferential butt joint supported and aligned by a backing ring, as shown in the "Original design" view in Fig. 10. The cap was made of ASTM A234, grade WPA, steel; the pipe was made of ASTM A53, grade A, steel.

When it became apparent that the wall thickness of the pipe cap could be less than that of the pipe without adversely affecting service performance, the joint was redesigned as a joggled lap joint (see "Improved design", Fig. 10). The offset incorporated in the pipe for the redesigned joint took the place of the backing ring previously used and furnished a locating surface for the cap. The redesigned joint was submerged-arc welded under the same conditions as those for the original joint (see table with Fig. 10), except that only two passes were required, rather than three.

Cost reduction was realized from elimination of the backing ring, from the saving in material resulting from the use of



Joint type	Joggled lap
Weld type, original design	Square-groove, with backing ring
Weld type, improved design	Modified single-V-groove, with integral backing
Joint preparation:	
Original design	Backing ring machined
Improved design	Cap end machined, pipe end reduced
Electrode wire	1/8-in.-diam EL12
Flux	F62
Welding position	Flat (horizontal-rolled pipe)
Welding voltage	25 to 26 v
Welding current	350 to 410 amp, dcsp
Welding speed	18 to 20 ipm
Number of passes, original design	Three
Number of passes, improved design	Two
Power supply	40-v, 600-amp transformer-rectifier (constant-voltage)
Fixturing	Chuck-type turning rolls; alignment clamps for tack welding

Fig. 10. Cap-to-pipe weldment for which over-all cost was reduced 35% by joint redesign that replaced a backing ring by an offset in the pipe (Example 53)

thinner pipe caps, and from the elimination of one circumferential welding pass. The change in joint design led to a saving of approximately 35% in total factory cost.

All joints were inspected visually and radiographically to check for full penetration and absence of slag inclusions. The rejection rate was less than 1%.

In multiple-pass welding of thick sections of steel, substantial savings in both material and labor can be realized by redesign of a joint to eliminate a backing strip, as in the application described in the following example.

Example 54. Change From a Single-V-Groove Weld With a Backing Strip to a Double-V-Groove Weld With a Welded-in Center Spacer Rod, That Reduced Costs and Distortion (Fig. 11)

Figure 11 shows a 120-in.-long steam-drum shell course, roll formed from 5-in.-thick ASTM A515, grade 70, steel (0.35% max C), with a welded longitudinal seam.

Originally, the butt joint for this seam was of single-V-groove design, and was welded with the use of a backing strip (see "Original design" in section A-A in Fig. 11). This joint design was unsatisfactory. Fit-up and removal of the backing strip were time-consuming operations, and welding from one side distorted the weldment.

The joint was changed to the double-V-groove design shown as "Improved design" in section A-A in Fig. 11. This change resulted in the need for much less weld metal; the need for a backing strip was eliminated; and distortion was reduced by sequential deposition of weld beads on the inside and outside of the joint. The amount of back gouging needed was less than that required to remove the backing strip from the single-V-groove weld. As a result of these improvements, electrode, flux and labor costs were reduced by 46%, and total cost of welding was reduced by 62%.

Operating conditions and costs for welding joints of the original and improved designs are given in the table with Fig. 11. Welding procedures and postweld operations for the two designs are described below. For both designs, the shell courses were hot roll formed into a cylinder and descaled, and the joint grooves flame cut.

Original Design. The single-V-groove joint was preheated to 175 F with a propane torch, the backing strip was installed, and the temperature of the joint was raised to 250 F. At least two root passes were made, using shielded metal-arc welding. This operation was followed by depositing six single-pass layers, each ⅛ in. thick, by single-electrode submerged-arc welding. Tandem submerged-arc welding was used to complete the weld, single-pass layers ⅛ in. thick being deposited to a weld level of 1½ in., followed by two-pass (split) layers ⅛ in. thick. Then the backing strip was removed by air carbon-arc gouging and grinding, and back welding was done, as required, to provide a flush joint.

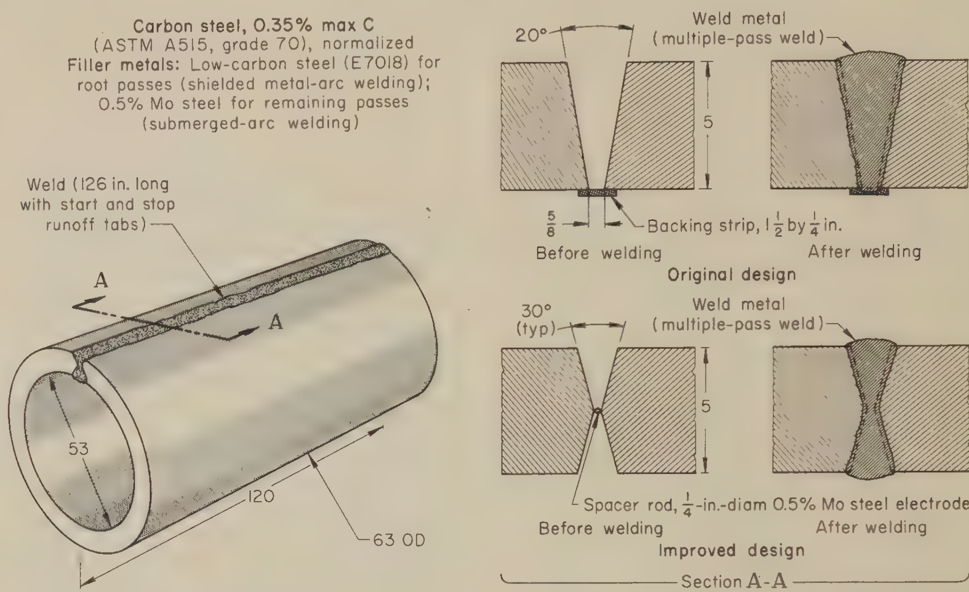
Improved Design. The double-V-groove joint was also preheated in two stages (175 F and 250 F) with a propane torch, except that instead of a backing strip being installed between stages, a spacer rod of ¼-in.-diam 0.5% Mo steel electrode material was tacked in place and seal welded by the shielded metal-arc process. Shielded metal-arc welding was used also for root passes. The first increment of single-electrode submerged-arc welds consisted of eight ⅛-in.-thick single-pass welds on the outside of the weldment. The workpiece was rotated 180°, and the joint was back gouged by air carbon-arc gouging and ground to a radius of ¼ to ⅜ in. The first increment of welding on the inside of the joint consisted of ⅛-in.-thick single-pass welds to a 1½-in. level, using single-electrode submerged-arc welding. Then the workpiece was again rotated 180°, and the remainder of the outside welding was completed using tandem submerged-arc welding to deposit two-pass (split) layers of ⅛-in. thickness.

After a final 180° rotation of the workpiece, the inside welding was completed using the same sequence of two-pass tandem submerged-arc welds of ⅛-in. thickness.

Postweld Operations. After having been welded, the shell courses incorporating both joint designs were examined radiographically. This was followed by stress relieving at 1150 ± 25 F for 1 hr per inch of thickness. Finally, welds were ground smooth.

Shell courses of both designs were welded in conformity with qualifications set forth in Section IX of the ASME Boiler and Pressure Vessel Code.

The example that follows describes an application in which both the workpiece and the joint were redesigned, and the welding process was changed,



Cost item	Joint design: Original	Joint design: Improved
Comparison of Costs per Weldment		
Electrode and flux per foot of weld(a)	$ 7.69	$ 4.14
Welding labor and overhead per foot of weld(b)	13.28	7.18
Total cost per foot of weld	$ 20.97	$ 11.32
Length of weld (including runoff tabs at ends), ft	10½	10½
Total welding cost per weld	$220.19	$118.86
Labor and overhead for installing and removing backing strip(c)	96.00	.....
Total cost per weldment	$316.19	$118.86

Cost Factors for Both Joint Designs

Weight of electrode and flux deposited per hour	15.6 lb
Weight of electrode and flux deposited per foot of weld:	
Original design (single-V-groove)	26 lb
Improved design (double-V-groove)	14 lb
Deposition efficiency	98%
Electrode and flux cost per pound	$0.29
Labor and overhead cost per hour	$8.00
Time for installing and removing backing strip (original design)	12 hr

Welding Conditions for Both Joint Designs

Joint type	Butt
Weld types	Single-V-groove (original); double-V-groove (improved)
Welding position	Flat(d)
Arc starting	Touch and retract
Preheat	175 F, then 250 F (propane torch)
Interpass temperature	500 F
Postheat	1150 ± 25 F (furnace), 1 hr per inch of section
Root passes (shielded metal-arc welding):	
Power supply	300-amp motor-generator
Electrode	3/16-in. E7018
Current and voltage	250 amp, dcrp; 24 v
Intermediate passes (single-electrode submerged-arc welding):	
Power supply	900-amp motor-generator
Electrode wire	7/32-in.-diam 0.5% Mo steel(e)
Current and voltage	700 amp, dcrp; 30 v
Travel speed	20 ipm
Final passes (tandem submerged-arc welding)(f):	
Leading head:	
Power supply	900-amp motor-generator
Electrode wire	7/32-in.-diam 0.5% Mo steel(e)
Current and voltage	800 amp, dcrp; 30 v
Trailing head:	
Power supply	1000-amp transformer
Electrode wire	5/32-in.-diam 0.5% Mo steel(e)
Current and voltage	700 amp, ac; 35 v
Travel speed	30 ipm

(a) Pounds of electrode and flux deposited per foot, multiplied by cost per pound of electrode and flux, divided by deposition efficiency. (b) Pounds deposited per foot, divided by pounds deposited per hour, multiplied by labor and overhead cost per hour. (c) 12 hr at $8 per hour. (d) Workpiece supported on one power roll and one idler roll. (e) Electrode wire contained 0.11 C, 0.50 Mo, 0.85 Mn, and was used at a 1-to-1 ratio of wire to flux. (f) Tandem welding head was mounted on a boom-type manipulator.

Fig. 11. Steam-drum shell course for which redesign of the longitudinal butt joint, from one for a single-V-groove weld to one for a double-V-groove weld, eliminated the need for a backing strip and reduced cost and distortion (Example 54)

to eliminate the need for backing bars, which unavoidably entrapped slag.

Example 55. Elimination of Backing Bars To Avoid Entrapment of Slag (Fig. 12)

A 12-ft-long header assembly for a large high-pressure heat exchanger was manufactured to Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code, under the rules for spot radiography (paragraph UW-52). These rules provide that one spot (with a minimum length of 6 in.) shall be examined in the first 50 ft of welding in each vessel, and one spot shall be examined for each additional 50 ft of welding or fraction thereof.

As originally designed (see view at upper left in Fig. 12), for manual flux-cored arc welding from the outside, the assembly consisted of four ASTM A515, grade 70, steel components and was welded at corner joints that incorporated backing bars, as shown in section A-A in Fig. 12. It was difficult to ensure a uniformly tight fit of the backing in the joint. Under radiographic inspection, slag, which ran between the backing bars and the adjacent 1½-in.-thick components, was revealed.

The problem was eliminated by redesigning the header assembly for automatic submerged-arc welding without backing bars. The redesigned assembly, shown in the upper right view in Fig. 12, consisted of two 1½-in.-thick ASTM A515, grade 70, channels formed in a press brake. The two components were welded at two longitudinal butt joints of the double-V-groove design shown in section B-B in Fig. 12.

For this improved design, the welding was done by use of a boom-mounted automatic welding head. The formed channels were held stationary while the welding head was advanced along the joints. First, root passes were made along the inside grooves of the two joints, then filler passes were made along the outside grooves. After the root passes, the outside grooves were machined-out to sound metal before the filler passes were begun.

Welding conditions for both designs and processes are compared in the table that accompanies Fig. 12. As this comparison shows, a major benefit of the change to two-piece design was that only about one-third as many filler passes were required for the entire weldment (ten passes, as compared with 28 to 32 passes for the original, four-piece design).

In the manufacture of horizontal shell-and-tube liquid coolers, as described in the following example, the use of backing rings was permissible under code requirements, but was avoided because the space occupied by the rings would necessitate a reduction in the number of tubes in the tube bundle, thereby impairing the efficiency of the unit. Backing rings were eliminated and melt-through was avoided by a combination of joint design, welding procedure, and special training of the welder.

Example 56. Joint Design and Welding Procedure That Gave Complete Penetration of a Joint Accessible Only From the Outside, Without the Use of a Backing Ring (Fig. 13)

Fabrication of heat exchangers for condensing or evaporating the refrigerant used in refrigeration equipment involved welding the heat-transfer chamber directly to the tube sheet. The chamber consisted of a cylindrical open-top shell and, when welded to the tube sheet, formed a pressure vessel completely enclosing the tube bundle, as shown in Fig. 13.

Because the inside of the vessel was inaccessible both for welding and for weld inspection, a major problem was that positive assurance could not be obtained that complete joint penetration had been effected, as required by Section VIII of the ASME Boiler and Pressure Vessel Code. When the entire weld was made by the submerged-arc process, complete penetration without melt-through was not obtained consistently when the joint was prepared by grooving the tube sheet for a single-V-groove and fillet weld (not shown in Fig. 13). The use of a backing ring was considered, but was ruled out because it would necessitate a reduction in the number of tubes in the bundle.

After experiments with several joint designs, a two-step welding procedure, using the joint shown in detail A in Fig. 13, was adopted. This design called for a single-bevel-groove weld with a fillet-weld reinforcement equal to the shell thickness.

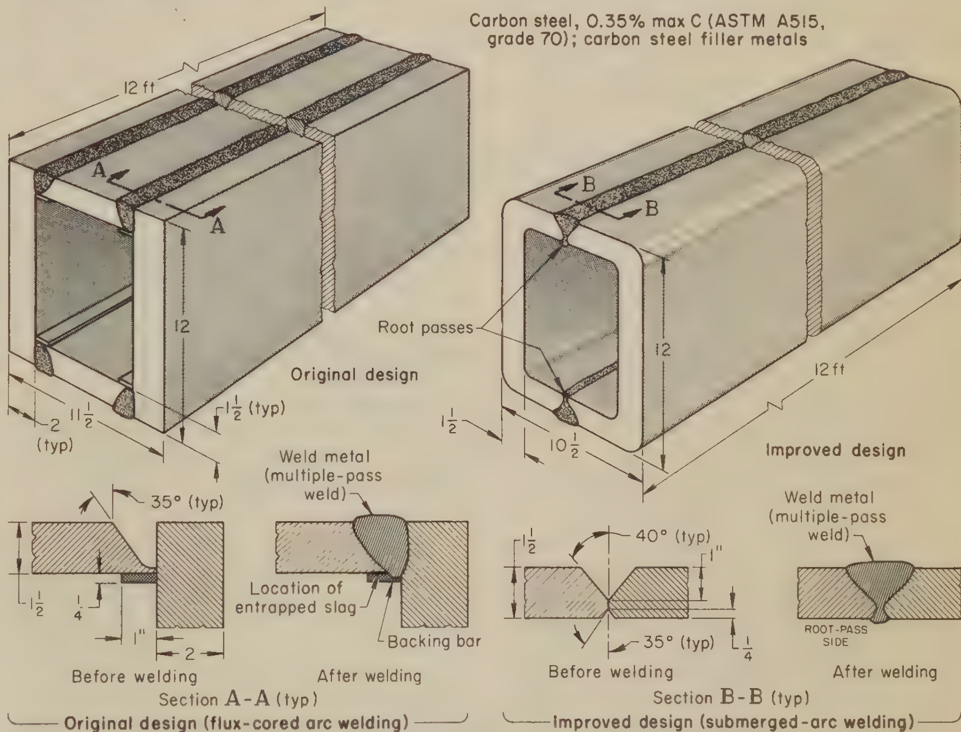
The two-step procedure consisted in the deposition of a root bead by shielded metal-arc welding, followed by a single filler pass by automatic submerged-arc welding. Welding conditions are given in the table with Fig. 13. The welding procedure, as well as the manual welder and the submerged-arc welding operator, had to be qualified in accordance with the rules of Sections VIII and IX of the ASME Boiler and Pressure Vessel Code. Melt-through and effective penetration were brought under control only by carefully following the welding procedures. Welders had to be specially trained to make the root pass satisfactorily. During submerged-arc welding, the electrode had to be carefully positioned to obtain proper sidewall fusion and to avoid undercutting.

Before welding, the joint areas were cleaned of scale and oil. Shell sheets had been sheared to size and beveled by oxyacetylene cutting before forming. In assembling the shell on the tube sheet, spacers were used to obtain the desired root opening and were removed after tack welding. No preheat or postheat treatment was used, normal room temperature (70 F) being the only requirement. The assembly was mounted on a conventional welding positioner for flat-position welding. After the root pass had been deposited, slag was removed by a needle gun, which consisted of a bundle of impact-driven steel quills capable of conforming to and abrading uneven surfaces. Surfaces were ground where necessary.

Automatic submerged-arc welding was performed from the carriage of a conventional manipulator on the same positioner and in the same position as the manual welding. Interpass temperature for this weld was 400 to 500 F.

After welding, the weld surface was cleaned by a needle gun, and the vessel was then tested for leaks by pressurizing it with dry air at 300 psig while submerged in water. Dry air was used because the interior of the vessel had to be dry for operation with refrigerants.

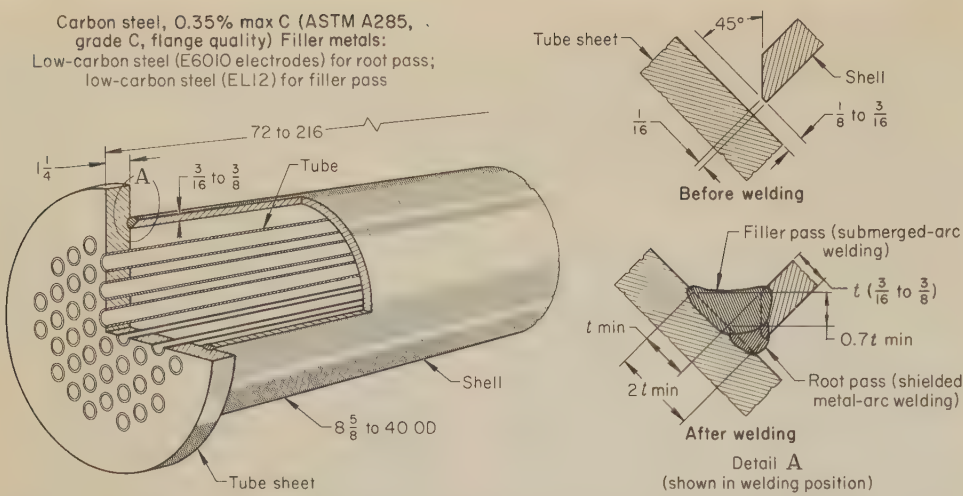
Flux-bed backing is provided by a separate backing flux or by the same flux used in welding. This eliminates



Item	Original design	Improved design
Welding process	Manual flux-cored arc	Automatic submerged-arc
Electrode	3/32-in.-diam flux-cored wire	3/32-in.-diam solid wire
Flux	....	F72
Welding position	Flat	Flat
Root-Pass Welding Conditions		
Welding current(a), amp	375 to 425	460 to 480
Number of passes per joint	1	1
Welding speed, ipm	6	8
Filler-Pass Welding Conditions		
Welding current(a), amp	375 to 425	400 to 600
Deposition rate, lb per hr	6	18
Number of passes per joint	7 to 8	5
Welding speed, ipm	10	22(b)

(a) Power supply for welding of both designs was an 80-volt (open-circuit) transformer-rectifier. (b) Welding speed for the first filler pass was 28 in. per minute.

Fig. 12. Heat-exchanger header that was redesigned to permit use of submerged-arc instead of flux-cored arc welding and thus to eliminate backing bars, which entrapped slag that registered in radiography as weld flaws (Example 55)



Item	Root pass	Filler pass
Welding process	Shielded metal-arc	Automatic submerged-arc
Power supply	400-amp motor-generator(a)	600-amp motor-generator(a)
Electrode	⅛-in. E6010	5⁄32-in.-diam EL12
Flux	....	F72
Electrode stickout, in.	....	½ to ¾
Welding position	Flat	Flat
Welding voltage	24 to 28	32 to 34
Welding current (dcrp), amp	80 to 120	300 to 350
Arc length, in.	⅛ to 3⁄16	⅜ to ½
Bead size, in. (approx)	¼	See drawing above
Welding speed, ipm	7 to 8	10 to 15
Number of passes(b)	One	One(c)
Deposition rate, lb per ft	....	1.2
Flux consumption, lb per ft	....	½ (approx); flux depth, ¾ in.

(a) Constant-current type. (b) Interpass temperature, estimated to be 400 to 500 F. (c) For shells 3⁄16 to ⅜ in. thick, as illustrated; additional passes were used on thicker shells.

Fig. 13. Refrigerant heat exchanger, and details of the tube-sheet-to-shell T-joint that required a manual root pass to ensure complete joint penetration without the use of a backing ring (Example 56)

the backing strip that is required for some types of complete-penetration welds. Beads deposited with flux backing require very little grinding or trimming to expose sound metal for deposition of the bead on the opposite (root) side of the joint. The resulting welds are of a quality that will pass radiographic inspection, as in the following example of this technique.

Example 57. Use of a Flux Bed as Backing for an Internal Bead in a Longitudinal Seam Weld (Fig. 14)

In submerged-arc welding of a longitudinal seam in a pressure vessel that was roll formed from 1 9⁄16-in.-thick carbon steel plate (ASTM A515, grade 70; 0.33% max C), a bed of welding flux was used as the backing for the internal weld bead, which was deposited first (see Fig. 14).

With the flux backing, there was no need to apply or remove a backing strip, and full penetration of the joint was obtained. Only minimum grinding was needed on the opposite (root) side to reach sound metal for deposition of the outside bead to complete the weld. The welding cost was less and production was faster than would have been possible by hand welding, semiautomatic welding, or submerged-arc welding with a removable backing strip.

The plate was laid out and gas cut to size before being roll formed. The edges of the double-V-groove butt joint (see detail at lower left in Fig. 14) were held in alignment for welding with either fitting blocks or tack welds applied to the outside of the joint. Maximum permissible misalignment was 1⁄16 in., and root opening varied from 0 to 1⁄16 in.

The workpiece was preheated, and then the first weld pass was made on the inside with the joint horizontal and on the bottom (6 o'clock position), as shown in Fig. 14. The welding head was on a long ram inside the shell. The flux was pressed against the back of the joint by the use of an air-inflated hose, as shown in Fig. 14.

After deposition of the inside weld bead, the opposite side of the joint was ground to sound metal, and the outside bead was deposited. Unfused flux was picked up by vacuum. Additional welding conditions are given in the table with Fig. 14.

Another application in which a flux bed was used as backing for the inside (first) weld pass in a longitudinal double-V-groove joint is described in Example 61 and illustrated in Fig. 28.

Flux Retention

In submerged-arc welding in the flat position, the layer of granular flux is maintained at a suitable thickness over the weld puddle. When a weld bead is to be deposited at or very close to the edge of one of the members, it is sometimes necessary to use flux retainers to provide mechanical means to contain the loose flux.

When using other positions in submerged-arc welding, a flux trough is used, or other means are provided, to prevent the loose flux from spilling away from the joint area.

In the following example, sheet edges were joined by welding in the horizontal position, using a flux trough that was part of the clamping fixture.

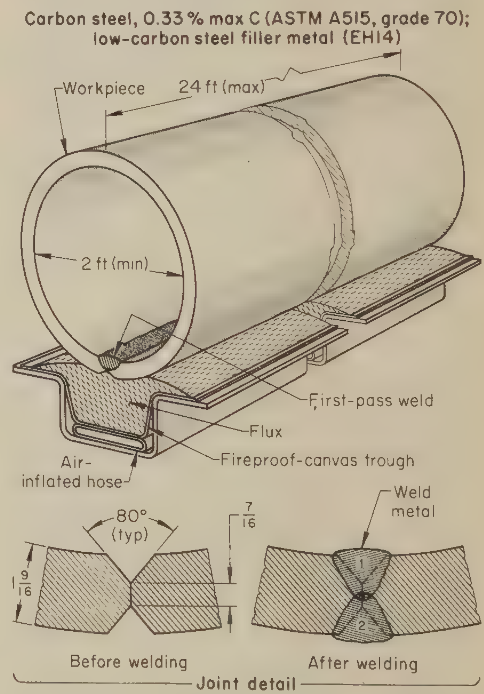
Example 58. Use of a Special Clamping Fixture With an Integral Flux Trough for Making a Horizontal Edge-Flange Weld (Fig. 15)

The two 1008 steel components of a warm-air-furnace combustion chamber were joined by a submerged-arc peripheral edge-flange weld while being held in the horizontal position between upper and lower rings of a special clamping fixture. As shown in Fig. 15, the lower clamping ring incorporated a flux-retaining trough to ensure flux coverage of the arc and the weld metal while the joint was being welded. The sheet-metal components of the chamber were aligned and located between the clamping rings, which were made of copper.

The welding-head carrier moved along the outside of a geared rack mounted on the underside of the table supporting the lower clamping ring (Fig. 15). The gear that engaged the rack was driven by a motor mounted on the welding-head support arm, and the geared rack served as a template to guide the welding head. The flux was introduced into the flux trough ahead of the arc, and unfused flux was removed by a trailing vacuum pickup. In addition to salvaging the unfused flux for reuse, the vacuum pickup cleaned the lower clamping ring well enough to receive the next chamber to be welded. The flux-delivery tube, the welding head, and the flux-recovery tube were guided from the same geared rack and were part of a single welding-head assembly.

An approximately round weld bead was produced along the flange edges, as shown in the joint detail for submerged-arc welding in Fig. 15. A 3⁄32-in.-diam electrode wire was used, to make alignment of the electrode tip with the flange edges less critical for maintaining a stable arc.

The welded joint was scraped clean and visually inspected by the welding operator. Later, the assembly was air-pressure tested under a waterhead of 6 in. When heated in service, the welded flange flexed to open slightly (see view at the right in the joint detail for submerged-arc welding in Fig.



Joint type	Butt seam
Weld type	Double-V-groove
Power supply	Two 100-volt (max), 1000-amp transformers, in parallel
Electrode wire	¼-in.-diam EH14
Electrode stickout	1 in.
Flux	F72 (20×D or 40×D)
Welding current and voltage:	
Inside bead	1200 amp, ac; 35 v
Outside bead	1550 amp, ac; 39 v
Number of passes	Two
Welding speed, both passes	7 ipm
Preheat	200 F, inside; 300 F, outside
Arc time (for 25-ft-long weld)	1½ hr, approx
Setup time (for 25-ft-long weld)	2½ hr, approx

Fig. 14. Use of a flux bed as backing in deposition of the internal weld bead in a longitudinal seam in a pressure-vessel shell (Example 57)

15), and expansion and contraction in heating and cooling were noiseless. There were no weld-related failures during prolonged use of the chambers. Conditions for submerged-arc welding are given in the table accompanying Fig. 15.

Experience With Other Welding Processes. The combustion chambers had previously been satisfactorily manufactured with the use of shielded metal-arc welding, but the rate of production was low. Welding speed was only 36 in. per minute, and direct-labor cost for welding each chamber was 20¢ — in comparison with 180 in. per minute and 5¢ per chamber by submerged-arc welding.

Before submerged-arc welding was adopted, alternative welding processes were evaluated. Gas metal-arc and gas tungsten-arc welding were not feasible, because there was no practical way to confine the shielding gas.

Resistance seam welding was tried, but the weldments were unacceptable because the electrode wheel indented the 0.036-in.-thick joint members, causing early service failures due to cracking. During flexing of the flanges while heating and cooling, cracks developed at the location shown in the view at the right in the joint detail for resistance seam welding in Fig. 15, a point of severe stress concentration. Unacceptable expansion and contraction noises, caused by the rubbing together of defectively welded sections of the seam, occurred during service. These defectively welded sections, which were up to ⅛ in. long, resulted from imperfect firing of the seam welder. They gradually became longer as adjacent sections of the weld failed from the expansion and contraction stresses in service.

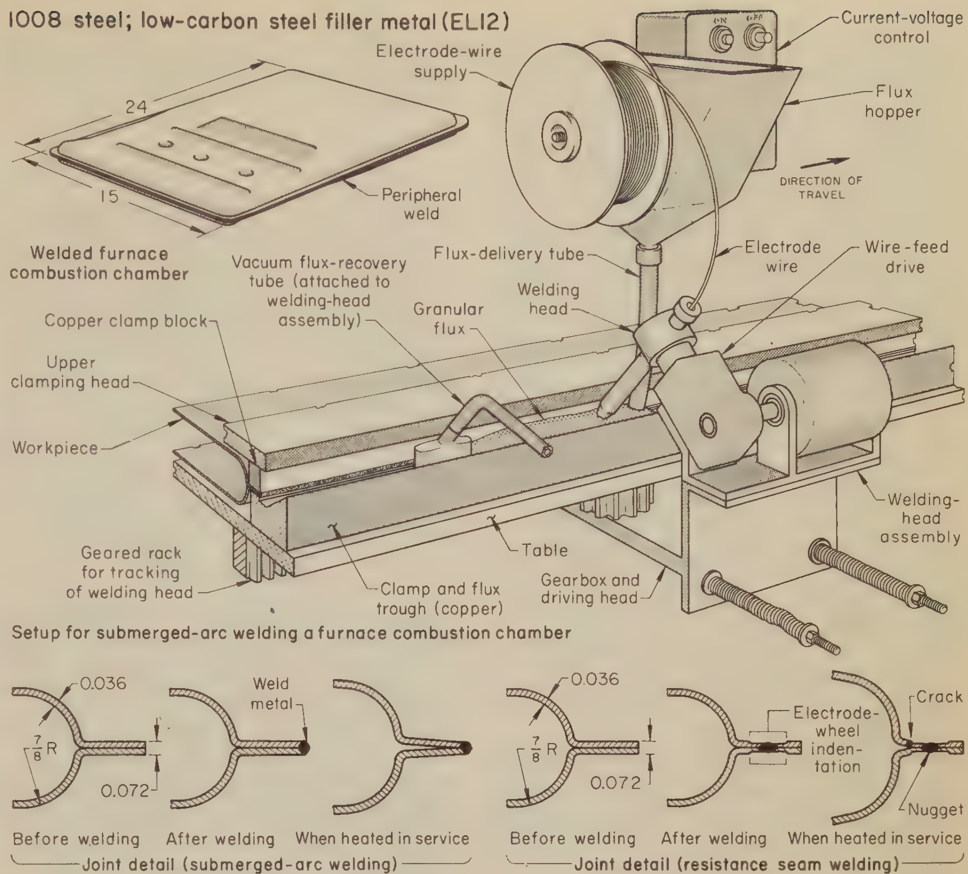
Circumferential welds (girth welds) present different problems in flux retention, depending on the orientation of the axis of the cylinder or other shape of workpiece being welded.

When the workpiece axis is horizontal, several techniques are effective in welding on small diameters. The normal electrode position, a few degrees from the vertical, to ensure proper solidification of flux and weld metal, helps to prevent spillage of loose flux. A nozzle assembly can be arranged to pour the flux directly on the arc, affording the flux less chance to spill. Also, a flexible strip of metallic or nonmetallic heat-resisting material may be attached to the nozzle assembly and positioned to ride over the workpiece ahead of the arc so as to retain the flux. Such an arrangement, incorporating a flexible dam, is shown in Fig. 16.

Figure 17 shows a flux dam that retained flux for two circumferential welds that were made simultaneously as the workpiece was rotated in a fixture. The portion of the dam that made contact with the flux was made of stainless steel for heat resistance, whereas the supporting arm was made of copper for good electrical conductivity. To prevent arcing between the workpiece and the dam, the copper arm contacting the workpiece was grounded, as shown in Fig. 17. (Submerged-arc welding with this flux dam was replaced by gas metal-arc welding, as described in Example 105, on page 102.)

Flux support may also be needed at the extreme ends of a cylindrical workpiece. This may be accomplished by either tack welding sheet-metal rings to the edges or providing flexible retainers that will ride along the edges. Both of these methods will permit welding close to the ends of the workpiece.

When making circumferential groove welds in the 3 o'clock position on work oriented with its axis vertical (horizontal welding position for large tanks or cylinders, or vertical pipe position), a flux trough is used, as described in Example 59 and illustrated in Fig. 25.



Conditions for Submerged-Arc Welding

Joint type .... Edge	Welding voltage .... 22 v
Weld type .... Edge-flange	Welding current .... 400 amp, dcrp
Joint preparation .. Die trimmed to square edge	Wire feed .... Automatic
Electrode wire .... 3/32-in.-diam EL12(a)	Welding speed .... 180 ipm(b)
Flux F62	Number of passes .... One
Welding position .... Horizontal	Direct-labor cost per chamber .... 5¢(b)

(a) Copper plated. (b) In shielded metal-arc welding, welding speed had been 36 in. per minute, and direct-labor cost per chamber had been 20¢.

Originally, chamber had been shielded metal-arc welded, but at lower speed and higher cost as shown in footnote (b), above. Resistance seam welding was unsatisfactory because cracking occurred when chamber was heated in service (see bottom right views, above).

Fig. 15. Use of a clamping fixture with an integral flux trough for submerged-arc welding of the furnace combustion chamber shown at top (Example 58)

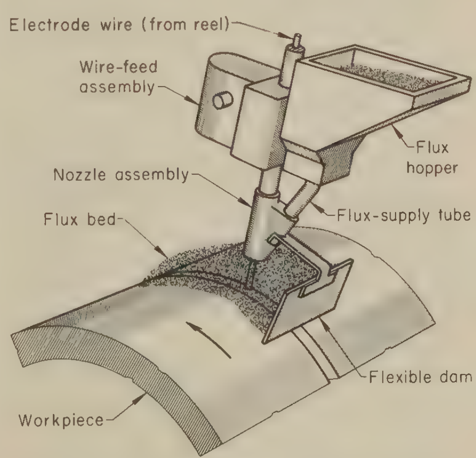


Fig. 16. Use of a flexible dam, attached to a nozzle assembly, for retention of flux in circumferential welding

Slag Removal

The size and shape of the weld bead can facilitate or hinder slag removal. Small beads cool more rapidly than large beads, thereby reducing the likelihood that slag will adhere to them. If the electrode melting rates are the same, the deposition of small beads is more economical than the deposition of large beads, because of the slag-removal factor. First-pass weld beads that are slightly concave (Fig. 18a) are much easier to remove slag from than are convex beads (Fig. 18b), which provide crevices for slag entrapment.

In general, slag removal is a function of groove width; if the slag bridges across the groove, removal is difficult. If split-weave technique is used, time for slag removal is minimal.

Because a circumferential weld on a small-diameter workpiece develops a large amount of local heat, slag removal can be made easier by training an air jet on the completed weld. When welding in the horizontal-rolled pipe position, the jet should strike the weld between the 2 and 3 o'clock positions.

Arc Starting

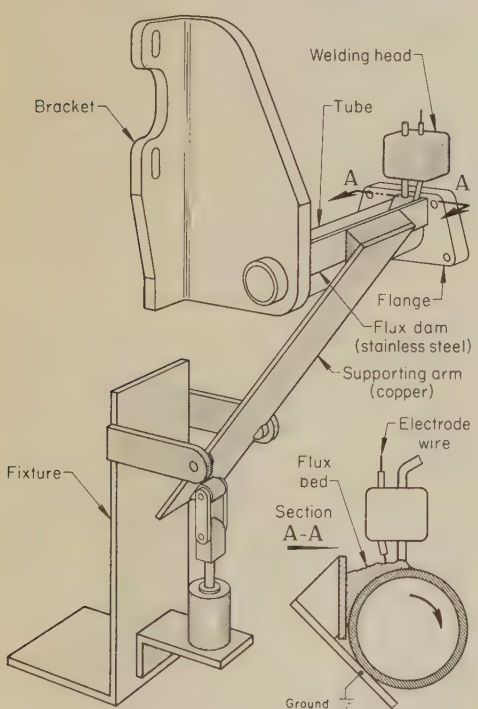
In submerged-arc welding, considering both semiautomatic and automatic methods, there are six methods of starting the arc: (*a*) high frequency, (*b*) wire retract, (*c*) fuse ball, (*d*) scratch, (*e*) pointed wire, and (*f*) carbon rod. Of these, the first three are used most frequently, employing either an alternating-current power supply or direct current with drooping voltage. The carbon rod is almost never used.

High-frequency starting requires the use of an accessory high-frequency, high-voltage unit. When the electrode wire is positioned about 1/16 in. away from the workpiece, the unit generates a spark that crosses from the wire to the workpiece and produces an ionized path through which the welding current can flow to establish the arc.

In wire-retract starting, the electrode wire is positioned to make electrical contact with the workpiece. When the welding current is applied, the wire is retracted by means of special equipment that reverses the wire-feed motor, drawing an arc of proper voltage. As soon as the arc is established, the motor reverses and feeds the wire at the desired speed.

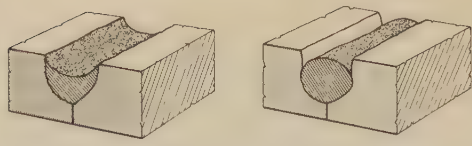
In fuse-ball starting, a tightly rolled ball of steel wool is placed between the end of the electrode wire and the metal to be welded. When the welding current is applied, the ball melts instantaneously, and the arc is established between the wire and the workpiece.

Scratch, pointed-wire and carbon-rod arc starting depend on the light contact between the electrode wire and the workpiece, or between a carbon rod and the workpiece, to develop an arc before the wire fuses to the workpiece. These methods of arc starting are generally not required when a constant-voltage power supply is used.



To increase production rate and reduce costs, submerged-arc welding, using this flux dam, was replaced by gas metal-arc welding, as described in Example 105, on page 102. Figure 39 on page 103 shows details of the welded joints, and the table with that illustration gives conditions for submerged-arc welding.

Fig. 17. Flux dam used to retain flux during the simultaneous deposition of two circumferential submerged-arc welds on a rotating workpiece



(a) Concave bead (easy slag removal) (b) Convex bead (difficult slag removal)

Fig. 18. Shapes of weld beads that facilitate and hinder slag removal between passes in multiple-pass submerged-arc welding

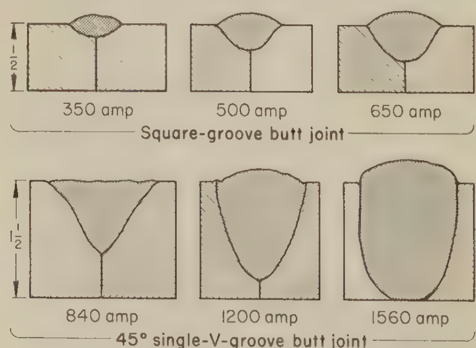
Current, Voltage, Speed and Other Operating Variables That Affect Weld Size and Quality*

Among the variables of submerged-arc welding that must be closely controlled to give welds of good quality, the most critical — in order of their importance — are welding amperage, current type (and, if direct current is used, polarity), welding voltage, and welding speed (travel speed). The combined effect of these factors on the base metal, the electrode wire, and the flux largely determines the nature and quality of the weld puddle and, ultimately, of the weld.

Other operating variables that affect weld size and quality are depth of flux layer, electrode stickout, electrode size, and the angle between the base metal and the electrode.

Welding current controls the rate at which the electrode is melted, the depth of fusion, and the amount of base metal melted. If the current is too high for a given travel speed, the depth of fusion or penetration will be too great, the weld may melt through the joint, and the weld heat-affected zone will be larger. Costs will be high because excessive power and filler metal will be consumed. On the other hand, too low a current will lead to inadequate penetration and inadequate reinforcement. The effect of current (amperage) on penetration and shape of butt welds in carbon steel plates ½ and 1½ in. thick is shown in Fig. 19.

*See also Fig. 51 to 59, in the Appendix to this article, beginning on page 73.



Welds were made in carbon steel plates ½ and 1½ in. thick, with 5/32-in.-diam electrode wire. For the ½-in. plate, voltage was 29 volts and travel speed was 30 in. per minute; the 1½-in. plate was welded at 40 volts and a travel speed of 12.5 in. per minute.

Fig. 19. Effect of welding current on penetration and configuration of two types of submerged-arc butt welds in two thicknesses of steel plate

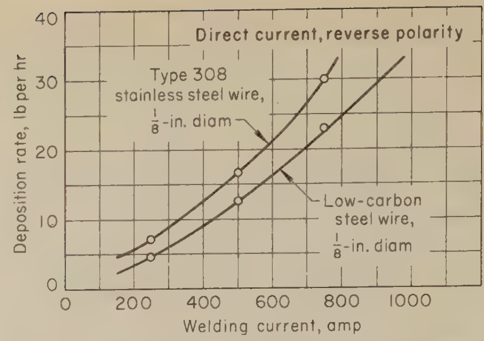


Fig. 20. Effect of current on deposition rates of stainless steel and low-carbon steel electrode wires, in welding with reverse-polarity direct current. (With straight polarity, deposition rates increase about 30 to 50%.)

The amount of weld metal deposited per unit of time is almost directly proportional to amperage. This is illustrated in Fig. 20, which shows the effect of amperage on deposition rates of ⅛-in.-diam low-carbon steel and type 308 stainless steel electrode wires. As Fig. 20 shows, about 2 to 3 lb of low-carbon steel wire is deposited per hour for each 100 amp of reverse-polarity direct current, whereas stainless steel wire is deposited at approximately a 30% higher rate because of its higher electrical resistance and lower heat capacity and melting temperature. (Deposition rate per 100 amp can be increased by increasing the stickout of the electrode wire beyond the contact tip, but this decreases penetration.)

In welding with direct current, deposition rate is 30 to 50% higher and penetration is shallower with straight polarity (electrode negative) than with reverse polarity (electrode positive). Thus, straight polarity may be preferred for surfacing and to prevent cracking of base metals that contain elements that promote hot cracking.

Alternating current is intermediate between straight-polarity and reverse-polarity direct current with respect to deposition rate and penetration, and is preferred where arc blow is troublesome. In multiple-wire, multiple-power welding, two arcs in close proximity are affected by each other's magnetic field. Arcs of like polarity flare together, and arcs of unlike polarity flare apart.

Welding voltage principally determines the shape of the fusion zone and reinforcement. As welding voltage is increased, the weld bead becomes flatter and wider, more flux is exposed to the arc, and flux consumption increases. With excessively high voltage, however, the arc breaks out from under its cover of liquid flux, air contacts the molten weld metal, and porosity results. The effects of increasing levels of voltage on the configurations of submerged-arc butt welds are shown in Fig. 21.

If the arc current is held constant and the arc voltage is low in relation to current, the base metal will not melt enough to give a good weld. The molten globules of metal passing from the elec-

trode to the workpiece cause continual short circuiting, which results in spattering and a high bead. As the arc voltage is increased, an optimum point is reached at which the arc no longer sputters but has a steady, sharp crackling sound. At this stage, good penetration will be obtained. If the arc voltage is further increased, the arc length will increase. The arc will be unstable and will make a wide, flat bead, usually with an undercut.

Increasing stickout will have essentially the same effect on bead shape as decreasing voltage.

Welding speed (travel speed) is an important variable governing the production rate and metallurgical quality of welds. Increasing the welding speed decreases the production time per unit on fillet welds, but has little influence on production time per unit length of groove welds for a given current and wire size. Welding speed also affects the rate of heat input. Increasing welding speed and decreasing current are two practical ways to lower heat-input rate.

Welding speed helps to determine the width and depth of the weld, as shown in Fig. 22. A weld bead consists partly of molten filler metal and partly of base metal melted by the arc. Base metal can constitute 15 to 60% of a submerged-arc weld, the percentage decreasing with welding speed. Excessively high welding speed decreases wetting action and increases the probability of undercutting, arc blow, weld porosity, and uneven bead shapes. Excessively low speed produces hat-shape beads that are subject to cracking; causes excessive melt-through; and produces a large weld puddle that flows around the arc, resulting in a rough bead, spatter, and slag inclusions.

Electrode-Wire Diameter. Decreasing the diameter of the electrode wire increases the pressure of the arc, thus increasing penetration and decreasing the width-to-depth ratio of the weld bead (see Fig. 23).

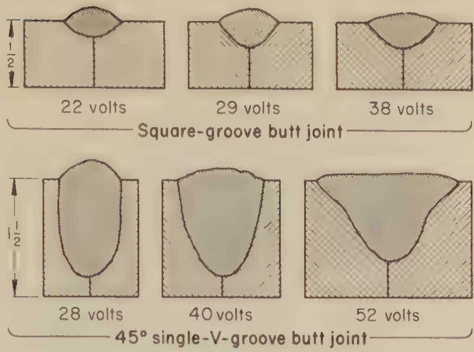
Depth of flux layer affects the shape and penetration of welds, as shown in Fig. 24. When the flux layer is too shallow (Fig. 24a), the arc is exposed and a cracked or porous weld results. When the flux is too deep (Fig. 24c), the result is peaked weld beads with above-average penetration. When the flux is neither too shallow nor too deep, very faint flashes appear around the interface between the electrode wire and the flux, and the weld bead appears as shown in Fig. 24(b).

Effect of Welding Position on Joint Design and Welding Conditions

Welding position during submerged-arc welding affects current, voltage, speed, joint design, and flux retention. As compared to the preferred flat-position groove welding, horizontal (or 3 o'clock) groove welding is done with lower current, higher voltage, and higher welding speed, as well as a different groove design. A flux trough is needed to retain the loose flux.

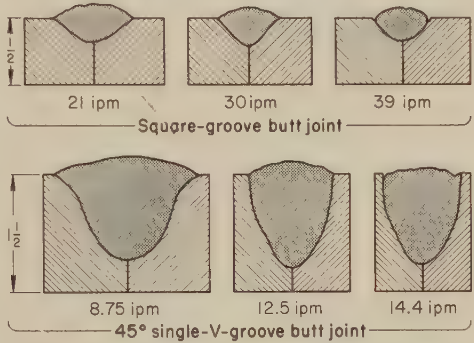
To compensate for the greater effect of gravity on the weld puddle and the molten flux, smaller beads are deposited in a weld groove that has its lower surface beveled at only a few degrees from the horizontal. Narrow, stringer beads are used. For the same thickness of work metal, at least twice as many passes are needed as for flat-position groove welding.

The effect of welding position on procedure is shown in the following example, in which it was not possible to do the welding in the preferred flat position.



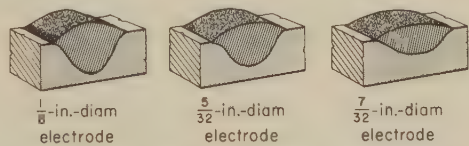
Welds were made in carbon steel plates ½ and 1½ in. thick, with 5⁄32-in.-diam electrode wire. For the ½-in. plate, welding current was 500 amp and travel speed was 30 in. per minute; the 1½-in. plate was welded at 1200 amp and a travel speed of 12.5 in. per minute.

Fig. 21. Effect of welding voltage on penetration and configuration of two types of submerged-arc butt welds in two thicknesses of steel plate



Welds were made in carbon steel plates ½ and 1½ in. thick, with 5⁄32-in.-diam electrode wire. For the ½-in. plate, welding current was 500 amp and voltage was 29 volts; the 1½-in. plate was welded at 1200 amp and 40 volts.

Fig. 22. Effect of welding speed (travel speed) on width and configuration of two types of submerged-arc butt welds in two thicknesses of steel plate



Welds were made on carbon steel plate by fully automatic submerged-arc welding, at 30 volts, 600 amp, and 30 in. per minute.

Fig. 23. Effect of electrode-wire diameter on width and penetration of surface welds

Example 59. Submerged-Arc Groove Welding in the Horizontal (Vertical Pipe) Position (Fig. 25)

A pipe nipple was submerged-arc welded to a forged steam chest oriented with the work axis vertical, so that the welding had to be done in the horizontal (vertical pipe) position. The nipple was made of 6-in.-ID forged Cr-Mo steel pipe with a 1-in.-thick wall. The two members were held in position by tack welding them to a machined backing ring, and a sheet-metal trough was clamped in place with a metal band to retain the loose flux, as shown in Fig. 25. The flux trough was wide enough to retain flux for the entire welding operation, so repositioning was not necessary. The backing ring was removed in a later operation. During welding, the workpiece remained stationary and the welding head was advanced. Welding conditions are given in the table with Fig. 25.

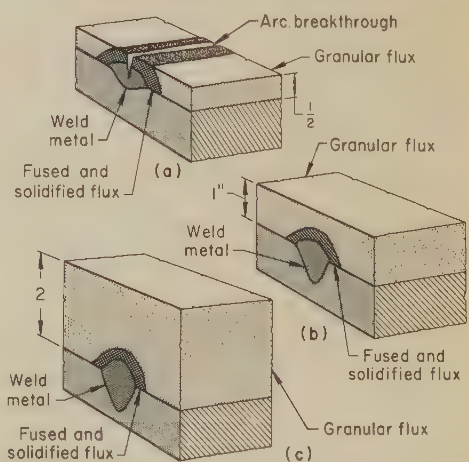
Although many of the welding conditions were the same as they would have been for welding in the flat (horizontal-rolled pipe) position, there were differences:

1 Electrode wire of smaller diameter (⅛ in. instead of 5⁄32 in.) was used.
2 Current was about 30% lower.
3 Voltage was about 1 to 2 volts higher, to flatten the bead.
4 Travel speed was about twice as high.
5 Flux depth was increased to maintain 1-in. minimum flux coverage as each bead was deposited (see detail of buildup sequence in Fig. 25).
6 A special joint design with a very small bevel angle at the bottom and a generous bevel angle at the top was used. (See Fig. 25 for joint designs and typical buildup sequences for welding in both the horizontal and the flat positions.)
7 The position of the electrode in relation to previously deposited weld beads was particularly important.
8 Closer control over current and welding speed was required.

Because of its drawbacks, submerged-arc welding in the horizontal position was used only on small-diameter assemblies, and then only when production schedules could be met in no other way. It was subsequently replaced on similar work by gas-shielded flux-cored arc welding.

Distortion

Because submerged-arc welding is characteristically well adapted to the joining of heavy sections at high current densities and correspondingly high heat inputs, it is more likely to cause distortion than are welding methods that employ lower heat input, depending, in part, on the number of weld layers deposited. However, the ability of submerged-arc welding to deposit large beads may be an advantage in reducing angular (transverse) distortion.



(a) Flux layer too shallow, resulting in arc breakthrough (from loss of shielding), shallow penetration, and weld porosity or cracking. (b) Flux layer at correct depth for good weld-bead shape and penetration. (c) Flux layer too deep, resulting in peaked weld bead with above-average penetration.

Fig. 24. Effect of depth of flux layer on shape and penetration of submerged-arc surface welds made at 800 amp

Longitudinal distortion, an important factor in the camber of welded girders, is greater for a single, large weld bead than for a series of small beads. Because reverse precambering is not difficult to apply, longitudinal distortion resulting from large weld beads can be readily controlled. In addition, torch straightening can be used after welding.

Angular distortion of a fillet-welded member increases with the number of weld layers. Thus, a ½-in. fillet weld deposited as a single layer by submerged-arc welding may exhibit only 1° distortion, whereas a four-layer deposit may be distorted as much as 3°.

Causes and Prevention of Weld Porosity

With few exceptions, the composition of the steels commonly welded by the submerged-arc process is not a major contributor to porosity. Exceptions are very high carbon contents, very low carbon contents (which can be corrected by using a silicon-killed electrode), and an excess of sulfur or sulfide inclusions. The last are particularly troublesome, because they generate gases that, when trapped in the molten metal, result in porosity.

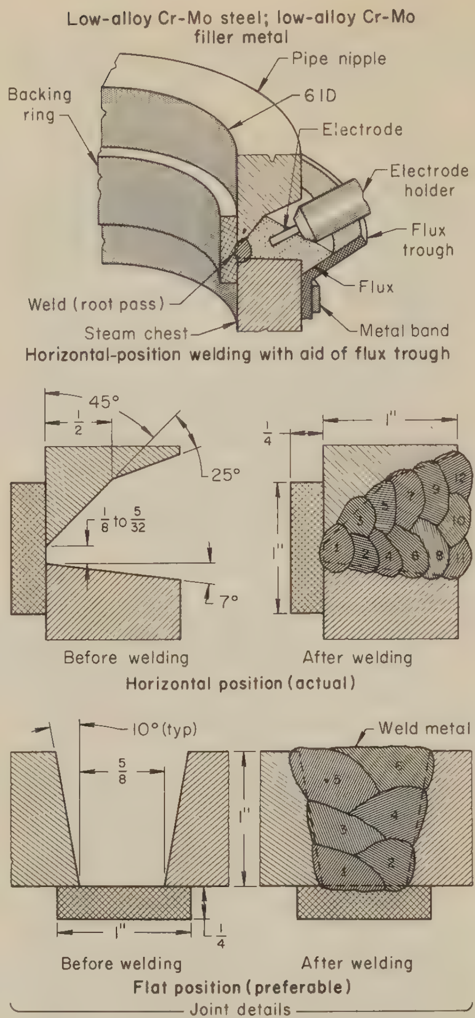
Sulfur-Rich Segregates. Even when the sulfur content of steels being welded does not exceed permissible limits, sulfur-rich segregates and inclusions may cause considerable hot cracking. Laminations of segregates in the base metal may cause porosity in the weld.

When it is necessary to weld steels containing sulfur-rich segregates, special procedures must be adopted. To minimize intermixing of base and filler metals, such steels usually are welded using low straight-polarity direct current, and large-diameter electrode wire. The use of high-manganese electrode wire will promote the formation of manganese sulfides — some of which, in turn, will be removed as part of the slag covering. Welding speed should be low enough to permit entrapped gases to escape through the molten puddle. Butt joints that normally would have square edges should be prepared as beveled joints, and on joints that are normally beveled, the bevel angle should be increased. Multiple-pass welding procedures should be used.

Hydrogen. To avoid porosity in the weld metal and cracking of the heat-affected zone of hardenable steel, submerged-arc weld metal should be deposited under low-hydrogen conditions. To obtain low-hydrogen conditions, the base metal, flux and electrode wire must be free of moisture, oil, rust and paint. Complete removal of all mill scale from the weld zone is imperative.

Joint Contaminants. Carbonaceous and other gas-producing contaminants in the joint are the most common cause of porosity. Joints must be cleaned of all contaminants, including moisture, rust, oil, paint and soil. Above all, the abutting edges of joints must be clean; cleaning only the outer surfaces of the joint is of little benefit.

Joint surfaces that have been prepared by machining or gas cutting can be welded satisfactorily provided they are not rusty or oil coated. Unprepared edges with normal "blue mill scale" generally can be welded without further preparation if the scale is not loose or flaky.



Conditions for Horizontal-Position Welding(a)

Joint type	Circumferential butt
Weld type	Modified J-groove
Joint preparation	Machining
Electrode wire	⅛-in. diam (b)
Flux	Neutral; size, 20×200
Electrode stickout	¾ to 1 in.
Welding position	Horizontal (vertical pipe)
Voltage	28 to 30 v
Current	325 to 350 amp, dcrp
Travel speed	20 to 25 ipm
Flux consumption per hour	10 to 15 lb
Deposition rate	10 to 12 lb per hr
Number of passes	12 to 14
Power supply	45-volt, 600-amp transformer-rectifier (constant-voltage type)
Preheat	400 to 450 F
Postheat(c)	600 F, 2 hr; 1250 F, 2 hr

(a) See text of Example 59 for details of conditions that would have been different for flat-position welding. (b) Same composition as base metal (low-alloy Cr-Mo steel). (c) Stress relief.

The horizontal welding position was used instead of the preferable flat position in order to meet production schedules. Joint designs and buildup sequences for the two positions are compared in the illustration.

Fig. 25. Pipe nipple joined to steam chest by submerged-arc groove welding in the horizontal (vertical pipe) position, with the use of a flux trough (Example 59)

Although blue mill scale will not adversely affect weld quality, "red mill scale" (which is reddish-brown in color) has the same detrimental effect as rust. For best results, red mill scale should be removed from joint surfaces by a combination of power wire brushing and torch heating. The wire brush should be used for preliminary removal of scale, and, during welding, the torch should be directed at the joint ahead of the arc to provide a reducing flame and drive off all residual moisture. To be effective, the torch should heat the surface of the base metal to the range of 400 to 600 F.

Flux and Electrode Wire. Contaminants in the flux, notably moisture, dirt and mill scale, also contribute to weld porosity. These contaminants are more likely to be found in flux that is reused. Moisture can be removed by heating the flux for about one hour at 750 F.

Electrode wire also must be free of contaminants, although a very light coating of special lubricant that has been used to facilitate feeding will not result in weld porosity.

Flux coverage is of the correct depth when the light of the arc reflects on the electrode. When flux coverage is insufficient, the arc flashes through and may cause porosity. Insufficient flux cover is more likely to occur on circumferential welds than on flat welds. On small circumferential welds, it is often necessary to provide mechanical support to the flux around the arc [see discussion under "Circumferential welds (girth welds)", page 57]. Similarly, if slag spills off a weld that has not yet solidified, the weld may exhibit surface porosity. Corner welds and multiple-pass horizontal fillet welds are especially susceptible to surface porosity caused by flux spillage.

Tack Welds. For shielded metal-arc tack welds that will be covered with a submerged-arc weld bead, electrodes of class E6010, E6011 or E7016 should be used (the choice depending on the application), because they give adequate penetration and produce porosity-free deposits. With these electrodes, slag removal is easy. Defective tack welds must be removed before proceeding with submerged-arc welding.

Backward arc blow is a cause of porosity that is most often encountered in the high-speed welding of thin sheets, using direct current, although thicker work metal can be similarly affected. In sheet-metal welds, porosity from backward arc blow usually occurs in the last few inches of a weld, becoming progressively more severe as the end of the weld is approached.

Although arc blow can occur in any direction, backward arc blow is a most common cause of porosity. Backward arc blow can result from a variety of causes, including improper placement of the electrical ground, poor electrical contact at the ground due to mill scale, and the development of a secondary magnetic field caused by the welding cable being partially wrapped around the joint being welded and thereby diverting the arc.

Backward arc blow can be prevented by welding away from the location of the ground, by depositing a heavy tack weld at the finish end of a joint, by angling the electrode forward, by using alternating-current welding power, or by clamping the ground firmly to the workpiece and welding toward the closed end of the fixture. Fixtures for welding thin metal preferably should

be made either of copper or of some other suitable nonmagnetic material.

Poor joint fit-up can promote porosity and slag inclusions by allowing flux to become trapped between the bottom of the weld bead being deposited and the side of the joint opposite the bead. These defects may be subsurface, occurring in the root of the weld, or they may come through to the lower surface.

Slag inclusions due to poor joint fit-up occur most often in butt welds. In a butt weld, the joint may be backed by a backing strip, by backing flux, or by another weld. If the gap between the plate edges is 1/32 in. or more, flux will spill into the gap ahead of the arc. Therefore, to avoid inclusions, either the weld bead must penetrate the backing, or penetration must be reduced to allow the weld bead to clear the backing by at least 5/32 in.

Press-fitted joints are sometimes coated with white lead (basic lead carbonate) before the parts are pressed together. White lead (as do most other lubricants) becomes a gas-producing contaminant that may cause porosity, generally in the form of large holes at or near the end of the weld, or weld cracking. It is best to avoid press fits and to allow a gap of 10% of the plate thickness, not to exceed 1/32 in., or to knurl the edge of one workpiece, thereby providing a path for the escape of gas.

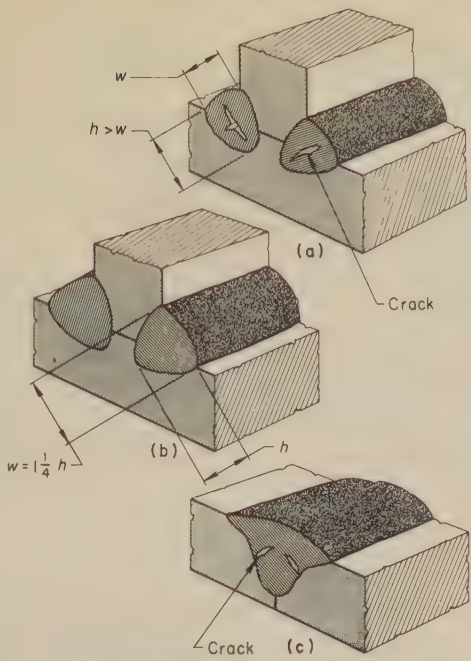
Porosity can also result from failure to remove scale or rust from lands of butt-joint groove welds.

Causes and Prevention of Weld Cracking

In submerged-arc welding of low-carbon steel less than 3/8 in. thick, weld cracking is seldom encountered. However, when thicker sections are welded — particularly those 2 in. or more in thickness — welds are subjected to more rapid cooling, accompanied with more severe cooling stresses. These stresses promote cracking, but precautionary measures can be taken to prevent cracking due to thermal stresses and thereby produce sound welds.

Causes of Cracking. Steel composition can be a cause of cracking, especially when the steel being welded is quench hardenable or exhibits hot shortness. Other factors that promote cracking include: (*a*) failure to preheat, or preheating at too low or too high a temperature; (*b*) heavy sections, which rapidly draw heat from the weld zone and thereby intensify thermal stress; (*c*) workpiece designs that impose a high degree of mechanical restraint on the weld area; (*d*) the presence of hydrogen-producing contaminants, such as moisture, in the weld zone; and (*e*) failure to postheat or adequately stress relieve the weldment.

Base-Metal Composition. The steels that are most suitable for welding by other major welding processes are equally well suited to welding by the submerged-arc process. Among the more weldable compositions are those of the carbon steels containing from 0.06 to 0.20% carbon, 0.35 to 0.80% manganese, and not more than 0.10% silicon, 0.035% sulfur, and 0.030% phosphorus. However, carbon may be increased to 0.25%, manganese to 1.10%, and silicon to 0.15% without affecting welding characteristics significantly. In contrast, special welding procedures are usually required when any one of the following elements exceeds the percentage indicated: 0.35% carbon, 1.40% manganese, 0.30% silicon, 0.05% sulfur, and 0.04% phosphorus. Further, the combination of a low manganese content, such as 0.25%, with a high sulfur content, such as 0.05%, will affect weldability adversely; manganese content must be increased to compensate for a high sulfur content.



(a) Fillet weld beads that have cracked internally because they are deeper than they are wide. (b) Fillet welds that are wider than they are deep, and hence are less susceptible to cracking. (c) Butt weld bead that has cracked because of its "hat" shape, caused by welding at too high a voltage or too low a speed.

Fig. 26. Effect of the shape of the weld bead on its susceptibility to cracking

Several structural steels, such as the grades covered by ASTM A36 and A283, are usually (although not always) welded without difficulty and without the use of special procedures, even though the specifications for these steels indicate upper limits of composition that exceed the optimum range. In practice, most steel sold to these specifications avoids the upper limits, particularly those for sulfur and phosphorus. However, when these steels are purchased to the ASTM specification, there is no guarantee that composition will invariably avoid the upper limits of those elements most likely to promote welding difficulties. Some ASTM specifications do not establish upper limits for certain elements (A283, for example, limits silicon and phosphorus contents only). Thus, the weldability of these steels cannot be predicted with assurance on the basis of specification, but depends on actual tests to qualify welding procedures.

In general, the importance of the chemical composition of the steel, as it affects welding quality, increases directly with increases in joint thickness and joint restraint.

Fillet Welds. To minimize internal-shrinkage stresses that could result in cracking, the fillet-weld bead should be at least 1¼ times as wide as it is deep. This is especially important for steels suceptible to cracking. Beads deeper than they are wide may crack internally, as shown in Fig. 26(a), and may present difficulties in slag removal. Bead contours and cross sections like those shown in Fig. 26(b) are satisfactory. These beads are 1¼ times as wide as they are deep, and the bead surface ranges from flat to slightly convex. The surface of the bead should not be concave; although concave welds present an attractive appearance, they can develop stresses that can result in cracks.

To avoid cracking in fillet welds joining steels of different compositions, the arc should be directed toward the steel with greater weldability, thereby minimizing interalloying of the less weldable steel.

Increasing stickout of the electrode wire (distance from tip of contact tube to workpiece) increases deposition rate and decreases penetration and interalloying. This helps to avoid cracking, but the shape of the weld bead is more difficult to control.

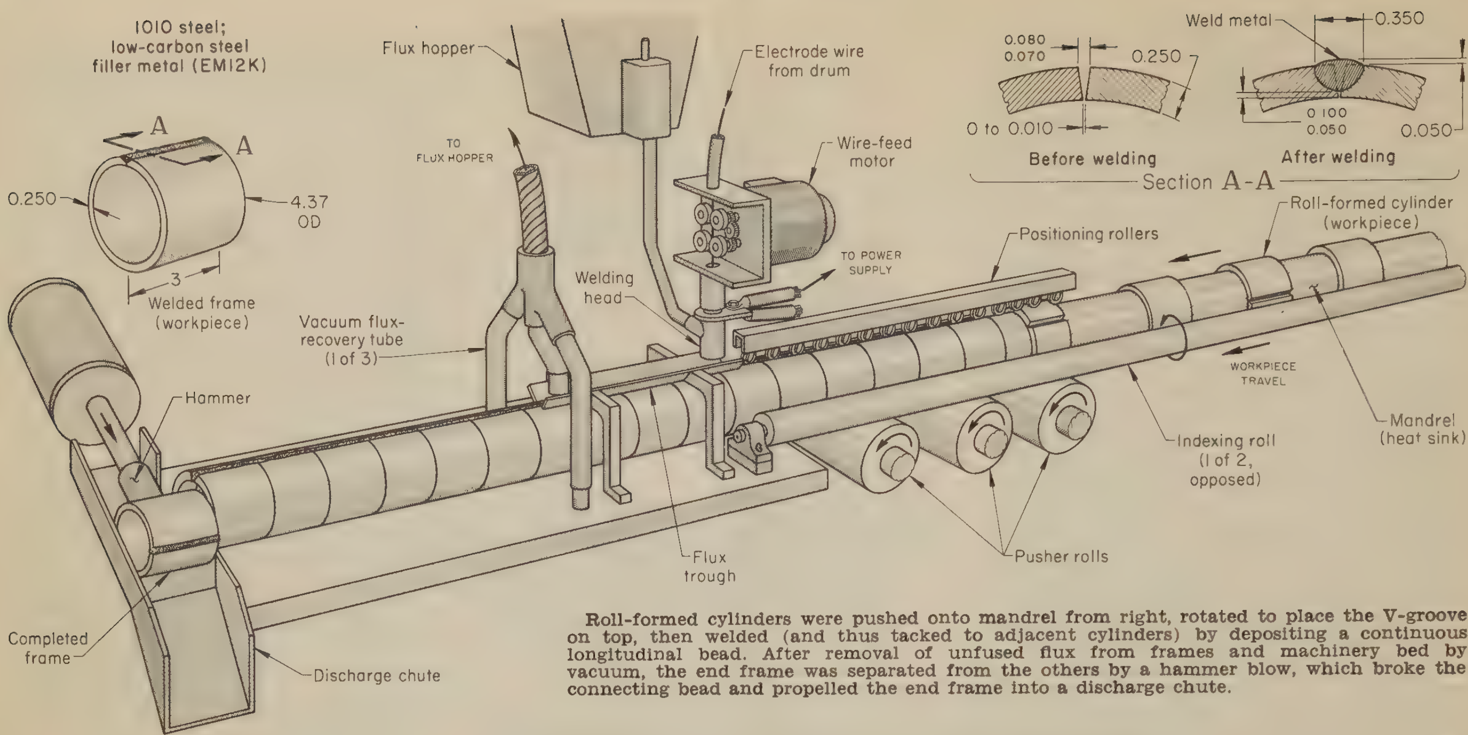
Butt Welds. Cracking in butt welds is less common than in fillet welds, because butt joints are usually less restrained. Under certain unfavorable conditions, however, cracking may occur. Internal cracking and slag inclusions are likely to occur when the butt joint has a groove angle that is too acute, especially for deep grooves that have zero root opening.

Recommended proportions of grooves for submerged-arc welding of steel are given on page 151. These groove proportions have been designed to ensure that the cross section of each weld bead can be at least as wide as it is deep.

For applications in which welds with 100% penetration are required in T-joints between thick plates, a low-hydrogen, shielded metal-arc electrode can be employed for the first pass on each side, to avoid an amount of penetration that will produce weld beads that are deeper than they are wide.

Hat-shape weld beads in butt joints, which result from welding at too high a voltage or too low a speed, may develop cracks at the locations shown in Fig. 26(c). Usually, the cracks can be prevented by reducing the voltage. Sometimes it is necessary to increase welding speed as well as to reduce voltage; this may require welding in two passes instead of one.

Another type of butt-joint weld bead that may crack is the one made during the first pass on the second side of a double-bevel-groove or double-V-groove joint. When the trough produced by back gouging the root-pass weld bead on the first side of the joint is deep and narrow, the first-pass weld bead on the second side of the joint will also be deep and narrow, and likely to crack. This can be prevented by making the back-gouged trough wide enough so that the first bead on the second side can be wider than it is deep. The depth of any one weld pass should not exceed its width. When necessary, a split-weave layer may be used.



Roll-formed cylinders were pushed onto mandrel from right, rotated to place the V-groove on top, then welded (and thus tacked to adjacent cylinders) by depositing a continuous longitudinal bead. After removal of unfused flux from frames and machinery bed by vacuum, the end frame was separated from the others by a hammer blow, which broke the connecting bead and propelled the end frame into a discharge chute.

Joint type	Butt	Flux	F72(c)	Welding position	Flat
Weld type	Single-V-groove	Number of passes	One	Arc length	¼ in.
Power supply	Motor-generator(a)	Current	420 amp, dcrp	Welding speed	51 ipm
Electrode wire	⅛-in.-diam EM12K(b)	Voltage	27 v	Preheat or postheat	None

(a) Output rating at 100% duty, 35 volts and 1000 amp. (b) This medium-manganese wire (0.85 to 1.25 Mn) was used to obtain weld metal with slightly higher manganese content than that of the base metal. (c) Containing manganese silicates.

Fig. 27. Automatic submerged-arc welding of automobile-starter frames, as a continuous process in a production-line station (Example 60)

Automatic Welding

In automatic submerged-arc welding, the welding equipment performs the entire operation (except for loading and unloading, which can be done manually or automatically) with little or no observation and adjustment of the controls by an operator. The electrode wire is fed automatically by means of an electric motor located in the welding head. The welding head also contains the necessary mounting and adjusting equipment for directing the arc at the work and maintaining proper arc length. The welding head is advanced by means of an automatic drive mechanism. It can travel over or alongside the workpiece, or be held stationary while the workpiece travels beneath or alongside it. Arc striking is also automatic. A flux-dispensing tube and hopper are usually attached to the welding head, together with the necessary conductors to provide the welding current. The equipment can deliver high welding currents.

Advantages. In automatic submerged-arc welding, precise control can be maintained on high-volume production, and more than one machine can be controlled by a single operator. Only periodic spot checking is required. The process is well suited to multiple-electrode welding, and also to the completely automatic handling of workpieces during loading and unloading. It also can provide higher welding speed than is controllable by a welder using semiautomatic equipment.

Limitations. Automatic submerged-arc welding requires the use of expensive equipment. In common with many automatic processes, justification for capital outlay for tooling and fixturing depends greatly on large production quantities and continuing demand. Automatic submerged-arc welding may be relatively cumbersome and inefficient when applied to small assemblies, because setup requirements, manipulation of additional equipment, and flux removal combine to offset the advantage of a high metal-deposition rate. Example 105, on page 102, discusses such a small assembly for which automatic submerged-arc welding was only marginally suitable.

Typical Applications. In terms of tonnage, steel line pipe used for transporting petroleum products represents a large application of automatic submerged-arc welding. In making the pipe, formed plate is fed into a cage of rollers that close the joint. The pipe travels through the welding station, where flux is automatically deposited on the joint, the weld is completed, and unused flux is returned to the flux-recovery system.

Although automation is the rule in submerged-arc welding, interruption of the arc between workpieces is ordinarily necessary. The completely mechanized operation described in the following example was unusual in that separate workpieces were welded continuously in sequence as if they were a single workpiece, without interruption of the arc and of deposition of the weld bead.

Example 60. Automated Continuous Welding of Roll-Formed Cylinders (Fig. 27)

Figure 27 shows essentials of the welding station in a continuous line for the production of automobile-starter frames from ¼-in.-thick 1010 steel flat stock by shearing, three-roll forming to cylindrical shape, and automatic submerged-arc welding. Welding conditions are given in the table that accompanies Fig. 27.

The V-groove of the longitudinal joint to be welded (see section A-A in Fig. 27) was that resulting from the roll forming of the sheared stock. After being washed, the roll-formed frames were transferred to a storage tower in the line, to assure continuity of supply for welding in the event of shear or forming-roll failure. From the storage tower, the frames were pushed, one after the other, onto a mandrel to form a tubelike arrangement for welding, as illustrated in Fig. 27.

The frames were oriented under the welding head by means of two parallel indexing rolls that rotated the frames until the joints were at the top, where a row of sharp-edge positioning rollers engaged and held the joints in alignment for continuous welding. Pushers advanced the aligned frames along the mandrel.

Through a single tube in the welding head, flux was fed to the joint from an overhead hopper while the electrode wire was motor-fed to the joint from a large cardboard drum. Just beyond the welding head were three vacuum tubes that picked up unfused flux for return to the overhead hopper. One tube was positioned directly above the weld; the other two were positioned on either side of the work to pick up flux that spilled off the frames onto the machinery bed.

The mandrel that supported the frames during welding also served as a heat sink. This, in combination with control of welding current and travel speed, resulted in weld penetration as shown in section A-A in Fig. 27, with no flash or melting on the inside wall of the frames.

Because the welded joint was continuous, the frames became automatically tacked together. They were separated by horizontal blows from a hammer, delivered as each welded frame moved beyond the mandrel, as shown in Fig. 27. The impact from the

hammer also served to break off much of the solidified flux adhering to the frames.

The separated frames passed through a cooler and then were expanded to finished size; the expanding action removed any remaining solidified flux and made internal machining unnecessary. Because the expanding operation was the most severe treatment the frames would receive, it served as a 100% check on weld quality. Failures were less than 2%. Weld-metal specimens had tensile strength of 75,000 psi.

Automatic submerged-arc welding can be used to produce high-quality internal and external longitudinal welds in cylinders and tanks that are roll-formed from plate, provided that the internal and external clearances permit the necessary manipulation of the welding head or heads. In some of these applications, including that described in the following example, it is advantageous to mount and transport the welding heads on booms to traverse the joint.

Example 61. Internal and External Longitudinal Welding of a Long Cylinder (Fig. 28)

The longitudinal double-V-groove butt joint in a 30-in.-OD cylinder 134 in. long, roll formed from 9/16-in.-thick steel plate, was welded by the automatic submerged-arc process in two operations, as illustrated in Fig. 28. The welded cylinder, which weighed about 1700 lb, had to undergo a fairly severe final forming operation, and for this reason, it was made from ASTM A515, grade 70, steel (0.31% max C), which has good formability and weldability.

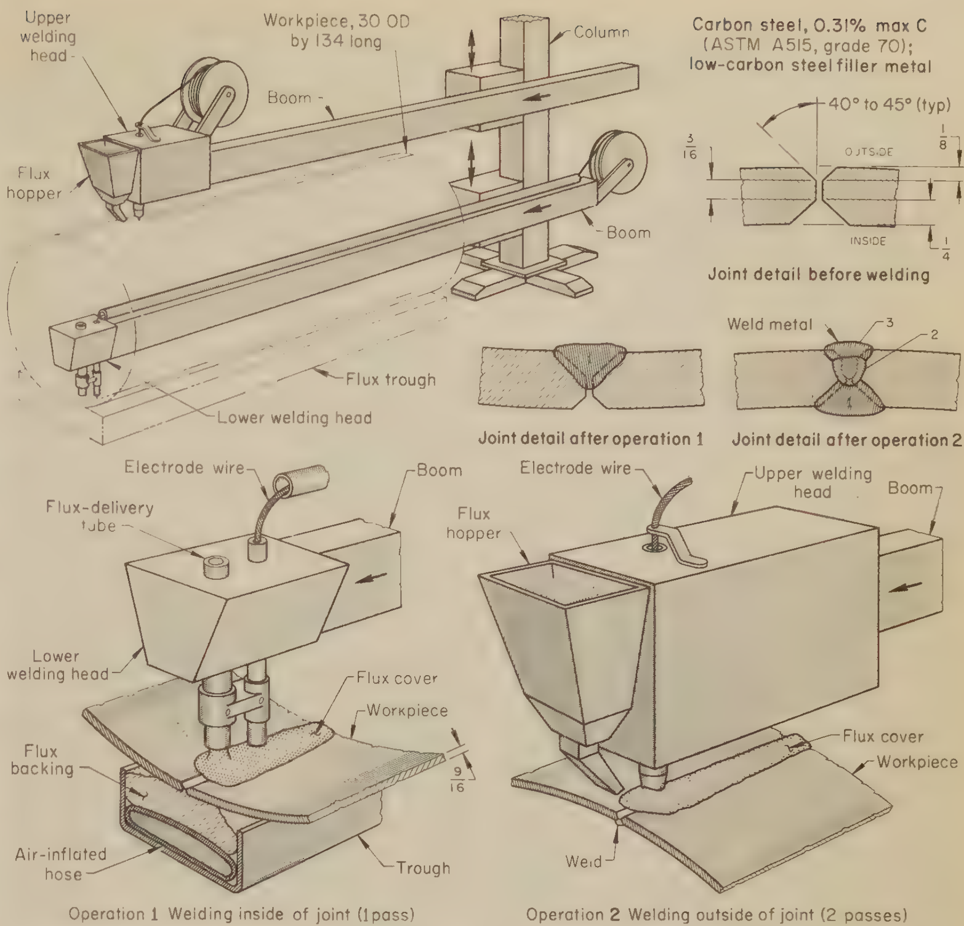
Submerged-arc welding was used because of its ability to yield sound welds with good penetration. An additional benefit of submerged-arc welding was that a flux-bed backing could be used in depositing the inside weld bead (the first operation), as shown in Fig. 28.

First, the plate was beveled on the edges to be joined, and roll formed to a cylinder, thus producing the double-V-groove butt joint shown in detail in Fig. 28. The outside of the joint was tack welded, and runout tabs (not shown in Fig. 28) were added to each end.

Two welding heads, mounted and transported on booms supported by the same column (see Fig. 28), were used for successively welding the inside and outside of the joint. The welding setup also included a trough in which an air-inflated hose was used to force granular flux against the outside joint groove, thus providing backing to contain the weld metal deposited on the inside of the joint, in the first operation. The flux trough also served as a workholding fixture.

The roll-formed cylinder was set on the flux bed with the joint at bottom center, the runout tabs were clamped down, and the air hose in the flux trough was inflated, forcing flux against the joint. Then the inside weld was deposited by the lower welding head in one pass. After the inside of the joint had been welded, the cylinder was removed from the flux trough and the outside of the joint was ground to sound weld metal. Then the cylinder was returned to the flux trough, with the joint at top center, for deposition of the external bead by the upper welding head, in two passes. The inside bead acted as the backing. Both operations required some observation by the welding operator to ensure alignment and to control welding speed and other operating variables (see table with Fig. 28).

The welding was done automatically with single electrode wires, using direct current with reverse polarity to control the bead shape and appearance and to produce consistent full penetration. Two 900-amp motor-generator sets connected in parallel supplied the welding current. The generators had a steep arc-voltage current characteristic. The electrode wire was low-carbon steel with copper coating to reduce



Joint type	Butt
Weld type	Double-V-groove
Joint preparation	Machining
Welding position	Flat
Power supply	Two 900-amp motor-generators, connected in parallel
Number of passes	Three

Item	Inside weld	Outside weld
Electrode-wire diam, in.	5/64	7/32
Welding voltage	37	38
Welding current (dcrp), amp	525-575	900
Welding speed, ipm	10	19
Welding time per bead, min	13.4(a)	7

(a) Exclusive of runoff tabs at the two ends of the cylinder

Fig. 28. Use of boom-mounted welding heads for two-operation automatic submerged-arc welding of the inside and outside of a longitudinal seam in a roll-formed cylinder. Trough contained flux for backing of the inside weld, and served to support the cylinder and helped maintain alignment for both operations. (Example 61)

electrical resistance at the contacting surfaces and to resist corrosion. The electrode wire and the contact jaws were kept clean and close fitting to ensure the maintenance of good electrical contact.

For each operation, flux was fed by gravity from a hopper at the welding head. Unmelted flux was returned by vacuum to storage after passing through a screen to remove slag. The flux was selected for good bead shape with reasonable penetration. It produced easily removed slag without significantly altering the composition of the weld metal.

The inside bead was ground flush with the cylinder wall, as required for subsequent operations. The welds were given a 100% radiographic inspection, and all production conformed to Section VIII, Div. 1, of the ASME Boiler and Pressure Vessel Code.

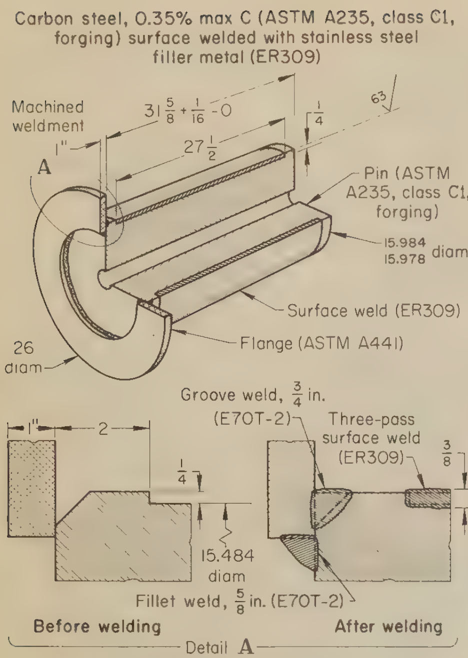
Surfacing Applications

The high deposition rates that are characteristic of submerged-arc welding can be adapted to various applications of surfacing — an operation in which weld metal is deposited on the surface of the workpiece to obtain resistance to wear or corrosion or to provide some other specific property or properties (also see the article on Hard Facing by Arc Welding, which begins on page 152 in this volume). The deposition of a corrosion-resistant overlay by submerged-arc welding is described in the example that follows.

Example 62. Surfacing a Low-Carbon Steel Trunnion Pin With Stainless Steel (Fig. 29)

The dam-gate trunnion pin shown in Fig. 29 was forged from ASTM A235, class C1, steel, which provided adequate strength for the application, but inadequate resistance to atmospheric corrosion. To provide protection from corrosion, a type 309 stainless steel overlay was deposited in an undercut section of the pin by three-pass submerged-arc welding, after a flange had been joined to the pin by flux-cored arc welding.

The undercut for surfacing was ¼ in. deep and extended nearly the full length of the pin, as shown in Fig. 29. To make the overlay, the pin was rotated in a 1000-lb welding positioner. The pin was supported by a shaft through its cored hole and by a mounting plate (not shown) that was tack welded to the end of the pin opposite the flange. A bridge over the positioner supported a carriage for the welding head. An improvised heater consisting of an insulated box and the burner from a floor furnace was used for preheating the pin and for interpass heating. In each pass, a bead ⅛ in.



Conditions for Surfacing

Weld type	Surfacing
Surface preparation	Machining ¼-in. undercut
Electrode wire	⅛-in.-diam ER309
Flux	Neutral; size, 48×100
Power supply	Two 35-volt, 350-amp transformers
Current	250 amp, ac
Voltage	25 v
Welding position	Flat(a)
Welding speed	17 ipm
Number of passes	Three
Preheat and interpass temperature	250 to 300 F
Arc time per pin	23¼ hr
Flux consumption per pin	40 lb
Weight of filler metal deposited per pin	40 lb

(a) Horizontal-rolled pipe position

Prior to surfacing, the groove weld and fillet weld joining the pin to the flange were deposited by semiautomatic flux-cored arc welding, using ³⁄₃₂-in.-diam E70T-2 electrode wire at 30 volts and 250 amp; welding time was 45 min.

Fig. 29. Dam-gate trunnion pin that was submerged-arc surface welded with stainless steel for protection against atmospheric corrosion (Example 62)

thick was deposited. Welding conditions are given in the table accompanying Fig. 29.

After the last pass, the pin was wrapped in 3-in.-thick fiber-glass and allowed to cool slowly for 12 to 14 hr. It was then machined to final dimensions, leaving a ¼-in.-thick coat of stainless steel on its shank.

Limited-Access Locations. When access to the area to be surfaced is limited, automatic submerged-arc welding is sometimes the most suitable and economical of the automatic welding processes, and gives more-uniform weld quality than does manual welding.

In the following example, two layers of weld deposit were applied to almost inaccessible sites in a steam chest, by automatic submerged-arc welding.

Example 63. Automatic Submerged-Arc Surface Welding of Internal Valve Seats (Fig. 30)

Four internal valve seats in a steam chest cast from low-alloy Cr-Mo steel were surface welded with stainless steel by the automatic submerged-arc process, as shown in Fig. 30 and detailed in the accompanying table. Manual welding was not feasible, because the only access to the valve seats was through holes 3½ to 5¼ in. in diameter, 15 to 22 in. above the seats (hole diameter and distance from the seats varied with the size of the chests, which varied in diameter and ranged from 8 to 12 ft in length).

The electrode wire was brought to the weld area through an electrically insulated copper guide tube (nozzle) with an angled head (see Fig. 30). The guide tube, lowered through and centered in the hole above each valve seat, was rotated at a fixed speed. During welding, flux, which was supplied manually or by gravity feed through the same hole in the steam chest, was retained by a carbon steel plug, which was machined out after welding. On each valve seat, a ⅜-in.-thick, two-layer surface weld was deposited in 10 to 14 passes. A typical 10-pass buildup sequence is shown in detail A in Fig. 30.

After each pass, a limit switch automatically stopped the welding and the rotation of the guide tube; then loose flux and slag were removed by a suction system, assisted by a pneumatic hammer that loosened the slag.

Gas burners were used to preheat the valve seats to at least 250 F before welding and to maintain this minimum temperature throughout the two-hour welding time required for completing each valve seat.

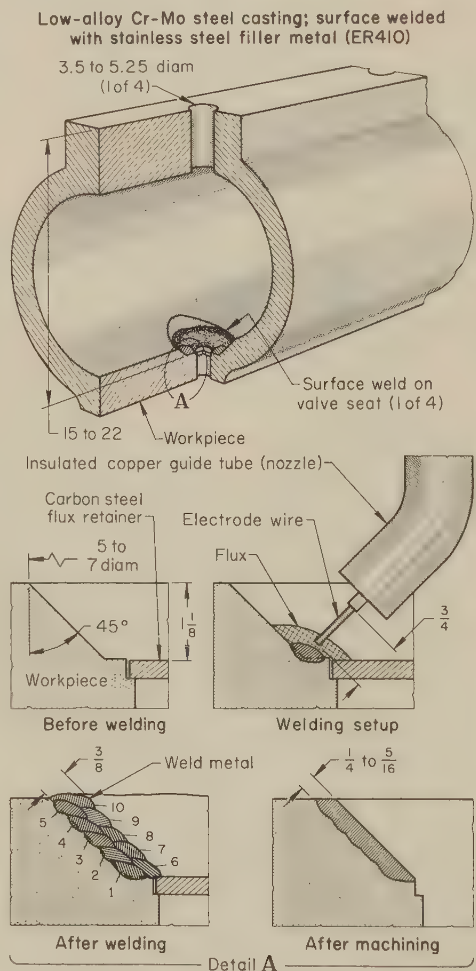
Electrode stickout was held constant at about ¾ in., and the guide tube was relocated upward ¼ in. and outward (horizontally) ⅛ in. for each pass. The arc for each pass was initiated by contacting the workpiece with the electrode and retracting the electrode automatically by means of the constant-voltage wire-feed system.

Because the valve seats were exposed to the erosive effects of high-temperature, high-speed steam flow, the weld deposit had to be sound, without voids, cracks, inclusions or oxides, and had to contain a minimum of 11% Cr. The electrode wire was ER410 (type 410 stainless steel), ⁵⁄₆₄ in. in diameter — the largest wire that could be fed through the guide tube.

By welding with straight-polarity direct current of 320 to 340 amp and an arc voltage of 34 volts, supplied by a constant-voltage transformer-rectifier, the small-diameter electrode wire provided a flat bead with good flow and clean overlaps.

The weld-surfaced parts were stress relieved by holding at 1250 F for about 10 hr. Then the flux retainers were machined out, and the weld deposit on each valve seat was machined to final dimensions (see "After machining" in detail A in Fig. 30). Inspection was carried out by visual examination and dye-penetrant testing. The rejection rate was less than 1%.

Two other automatic processes, gas tungsten-arc and gas metal-arc welding, had been evaluated for this application. Submerged-arc welding was chosen over the other processes because it required the least setup and cycle time, was easiest to apply through the limited-access hole, permitted greatest control of variables, and entailed the lowest initial and maintenance costs.



Process	Automatic submerged-arc welding
Weld type	Surfacing
Power supply	45-v, 600-amp constant-voltage rectifier
Voltage	34 to 35 v
Current	320 to 340 amp, dcsp
Electrode wire	⁵⁄₆₄-in.-diam ER410
Electrode stickout	¾ in.
Flux	Neutral
Welding speed	15 ipm
Number of passes	10 to 14
Preheat and interpass temperature	250 F min
Postheat (stress relief)	10 hr at 1250 F
Deposition rate	12 to 14 lb per hr
Flux consumption	12 to 15 lb per hr
Production time per valve seat	2 hr

Fig. 30. Portion of a steam chest in which four internal valve seats, accessible only through opposing holes, were surface welded as shown (Example 63)

Positioning the Welding Head in Relation to the Work. The deposition of surface welds often requires the use of complicated fixturing to position the workpiece and to guide the welding head over the surface contours that are to be overlaid. However, if the overlay is to be deposited on a surface of rotation, simpler fixturing may be required, as described in the following example.

Example 64. Surface Welding the Groove of a Large Sheave (Fig. 31)

The large low-carbon steel sheave (pulley) shown in Fig. 31 was used infrequently, and when not in use was exposed to the weather, which led to surface deterioration that caused the grooved rim to seize during operation of the sheave. To prevent this, the rim was surface welded with a three-layer deposit of stainless steel. Automatic submerged-arc welding, under the conditions listed with Fig. 31, was chosen, to obtain the best combination of deposition rate and soundness of deposit.

The sheave was gas cut from ASTM A36 steel plate 4½ in. thick, and the center hole was rough bored. The rim groove was then machined to the dimensions shown in the "Before welding" view in detail A in Fig. 31, and the sheave was mounted on a welding positioner.

So that the same welding conditions could be applied during the entire surfacing operation, the welding head was mounted on the frame of the positioner with fixturing that held the head in a fixed position with reference to the grooved rim. The sheave was rotated automatically on its axis to give a welding speed of 20 to 22 in. per minute. The overlay was deposited in three layers, each consisting of 36 passes; total thickness of the overlay was ¼ in. For the initial passes covering the central portion of the sheave groove, the sheave was in an upright position (with its axis horizontal). As the welding progressed toward the outside of the groove, the angle of the positioner was adjusted in increments to keep the work surface at the welding point within 30° of horizontal for each pass. The

same sequence of positioning was repeated to deposit the second and third layers of weld metal.

Initially, solid stainless steel electrode wire was used, but the overlay cracked severely on cooling. The cracking was caused by shrinkage stress in the first layer of the overlay, which was brittle because of dilution of its alloy content and increase in carbon content by diffusion from the carbon steel base metal. To increase the ductility of the first layer deposited, cored tubular electrode wire was used instead of solid wire. The cored wire consisted of a low-carbon steel tube filled with alloying and fluxing ingredients needed to deposit weld metal similar in composition to type 309 stainless steel. The cored wire gave a less penetrating arc, so that bead dilution and carbon diffusion were reduced, thereby eliminating the cracking during cooling.

The completed overlay was visually inspected, and then it was machined to final dimensions. The finished surface was dye-penetrant inspected; a few pinholes were the only flaws detected in the 40 sheaves processed. The pinholes were repaired by manual gas tungsten-arc welding and hand dressed.

Examples 153, 154, and 155 in the article on Hard Facing by Arc Welding describe the use of submerged-arc welding for deposition of wear-resistant alloys in surfacing oil-field drill collars, tractor rollers and idlers, and blades for shearing hot metal.

Multiple-Electrode Welding

In submerged-arc welding, deposition rate can be markedly increased by the use of a multiple-electrode welding system. These systems can be differentiated on the basis of three variables: number of electrodes, type of power connection used, and the position of the electrodes (tandem or transverse) with respect to direction of travel.

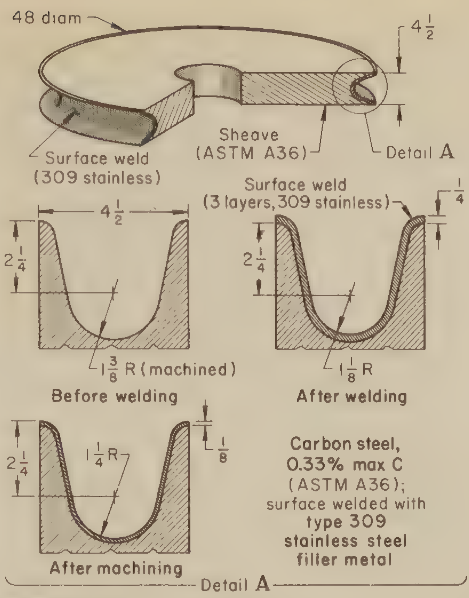
Number of Electrodes. Depending on the system selected, the number of electrodes in simultaneous operation can vary from two to four (see Example 67), or more.

Power connection may consist of a multipower connection, a parallel connection, or a series connection.

In a multipower connection, each electrode has its own power supply, welding head, voltage-control mechanism, and wire-contact assembly. Two-phase or three-phase power, and any combination of alternating and direct current, can be supplied to the electrodes. The welding ground is attached to the workpiece, and a voltage-control unit governs each welding head. With multipower connections, extra-high-speed welds can be made. With two-phase or three-phase power, magnetic effects permit better arc control and improved operation. The weld is narrow and deep-penetrating.

In a parallel connection, the electrodes are connected in parallel to the power supply, and attachment of the welding ground to the workpiece is conventional. One voltage-control unit governs the operation of a single welding head, which feeds both electrodes simultaneously. This is the only multiple-electrode welding system that requires only one welding head. Current densities are reduced, and penetration is less than that obtained with a multipower connection. A parallel connection is often used with electrodes in the transverse position to make extrawide welds for poorly fitted joints. With a parallel connection, the weld is much broader than it is deep.

In a series connection, two electrodes are connected in series, and two welding heads are used. Each electrode has a separate voltage-control unit and operates independently. One power-supply cable is connected to one welding head. The other



Process	Automatic submerged-arc welding
Weld type	Surfacing
Surface preparation	Machining
Power supply	750-amp, constant-voltage rectifier
Electrode wire	1/8-in.-diam cored 309 stainless
Flux	Proprietary
Welding position	Flat (within 30°)
Current	380 amp, dcrp
Voltage	30 v
Wire feed	Automatic
Welding speed	20 to 22 ipm
Number of weld layers	Three
Number of passes per layer	36
Total arc time per sheave	12 hr
Finishing	Machining to dimensions

During welding, the sheave was rotated in a three-ton variable-speed positioner, to the frame of which the welding head was mounted in such a way as to retain a fixed position relative to the groove being surface welded.

Fig. 31. Sheave with a rim groove that was surface welded with stainless steel, to prevent seizing in service (Example 64)

cable is connected to the second welding head, instead of to the workpiece, as in conventional welding. Welding current travels from one electrode to the other through the weld puddle and surrounding material. There is no connection between the power supply and the workpiece. Almost all of the power is used to melt the electrode, with little power entering the workpiece. With the electrodes in the transverse position, series connection produces a broad, shallow weld bead, and thus is well suited to the deposition of a surfacing overlay on a base metal with very little dilution. Deposition rates of 25 lb per hour are readily obtainable.

Electrode Position. With any of the three types of power connections, different effects can be produced by altering the position of the electrodes with respect to the direction of travel. Electrodes may be arranged in either the tandem or the transverse position; with three or more electrodes, other patterns are possible.

Usually, electrodes are arranged in the tandem position — that is, with one electrode following *behind* the other as they move in the direction of travel. (Welding with electrodes in the tandem position is sometimes referred to as tandem-arc welding.) With electrodes in the transverse position, one is positioned *alongside* the other as they move in the direction of travel.

For more complete coverage of power-supply systems, electrode positioning, electrical circuitry, phase-angle relationships, and other variables in the application of welding with multiple-electrode systems, the reader may refer to the following articles: D. E. Knight, Multiple Electrode Welding by "Unionmelt" Process, *Welding Journal,* Apr 1954, p 303-312; R. A. Kubli and H. I. Shrubsall, Multipower Submerged-Arc Welding of Pressure Vessels and Pipe, *Welding Journal,* Nov 1956, p 1128-1135.

In the example that follows, welding in the tandem position was used to butt weld thick plate in a pressure vessel.

Example 65. Tandem-Arc Welding of Pressure-Vessel Plates up to 8 In. Thick (Fig. 32)

Figure 32 shows the design of a single-V-groove longitudinal butt joint used in submerged-arc welding of thick-wall pressure vessels made of carbon or low-alloy steel. The minimum inside diameter of these vessels was 24 in., and the wall or plate thickness did not exceed 8 in. — an upper limit imposed by the need to accommodate the welding head in the joint.

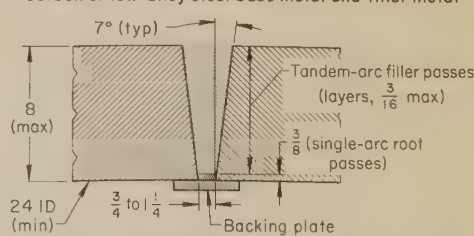
The edges that formed the joint groove were beveled by gas cutting to provide the 7° angle shown. Mismatch allowance after roll forming the plate was 1/16 in. max. Prior to welding, a backing plate was located at the base of the groove, as shown in Fig. 32. The root opening varied from 3/4 to 1 1/4 in., depending primarily on wall thickness and accessibility required by the welding head. Workpieces were preheated to 250 ± 50 F, to minimize distortion and prevent cracking.

For root passes to a depth of 3/8 in., a single electrode was used, and power input was reduced to a level that would avoid burning through the backing plate. The remainder of the joint was filled by two-electrode (tandem-arc) welding, using alternating current in both electrodes. The current input was increased to provide maximum speed of metal deposition.

Additional welding conditions are given in the table with Fig. 32.

Deposition rate can be further increased by preheating the electrode wire by electrical resistance to passage of the welding current. Resistance is increased by lengthening the path the current has to travel — that is, by lengthening the stickout (also called electrical stickout), which is the distance from the end of the contact tube to the weld puddle. In the next example, both the tandem-arc and the long-stickout heating methods for increasing deposition rate were used.

Carbon or low-alloy steel base metal and filler metal



Process	Automatic submerged-arc welding
Joint type	Butt
Weld type	Single-V-groove
Electrode wire	3/16-in.-diam carbon or low-alloy steel
Power supply	Transformers
Preheat	250 ± 50 F

	Single-arc root passes	Tandem-arc filler passes(a)
Current (ac), amp	500	750
Voltage	33	35
Welding speed, ipm	12	20

(a) Values shown are for each electrode.

Fig. 32. Longitudinal butt joint in a thick-wall pressure vessel that was tandem-arc welded after single-arc root passes had been made (Example 65)

Example 66. Deposition Rates in Welding With a Single Electrode, and With Tandem Electrodes Using 1-In. and 5-In. Stickouts (Fig. 33)

A cylindrical, high-pressure steam vessel 10 ft long, shown at upper left in Fig. 33, was roll formed from ASTM A515, grade 70, steel plate, 2½ in. thick. The joint edges were then machined or torch cut to make a 60° groove (see section A-A in Fig. 33), the joint was fitted up, and the sealing root pass was shielded metal-arc welded.

Automatic submerged-arc welding was then used to complete the joint from the outside. The joint was turned over and the root-pass bead was air carbon-arc gouged from the inside to expose sound submerged-arc weld metal, and the resulting groove was then submerged-arc welded to produce a smooth inside joint.

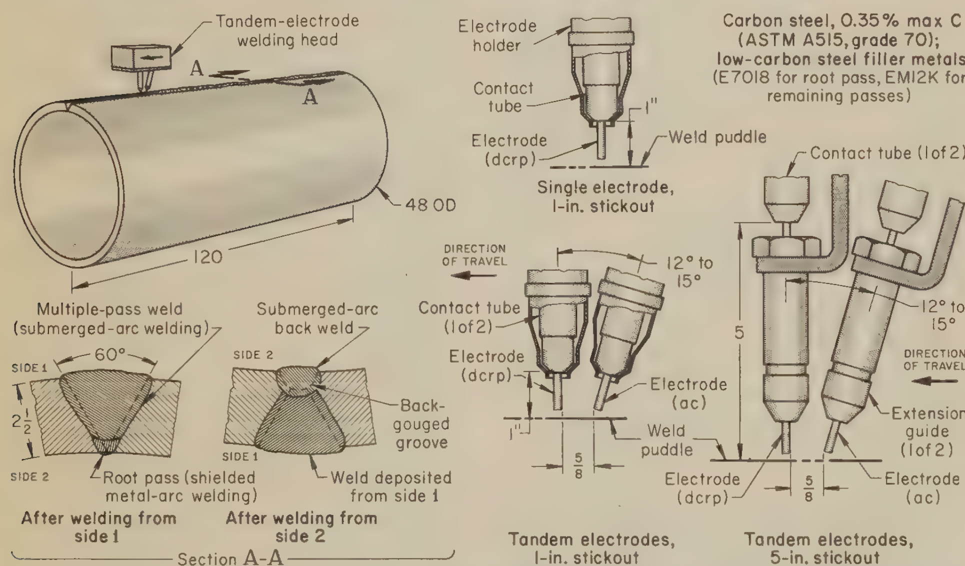
Twelve pounds of weld metal per linear foot was required to complete the longitudinal seam — 120 lb for the 10-ft length. When single-electrode submerged-arc welding was used, total arc time required per seam was 8.6 hr. To reduce this arc time, two other submerged-arc welding techniques were evaluated. In both techniques, following a single-electrode first filler pass, tandem-arc welding was employed for the first side of the joint, using a lead electrode with reverse-polarity direct current and a trailing electrode with alternating current. The difference lay in the length of the stickout of the electrodes: in one method it was 1 in. on both electrodes; in the other it was 5 in. on both electrodes, using extension guides (Fig. 33).

For the tandem-arc arrangement with 1-in. stickout, the total arc time for the joint was 4.6 hr, or about one half the time consumed by single-electrode welding. For tandem-arc welding with 5-in. stickout, arc time per joint was reduced to 2.8 hr, because of the increased resistance heating of the wire that resulted from the greater stickout. Operating details for the three welding procedures are given with Fig. 33.

Welding Position. When two or more electrodes are used to deposit filler metal, the flat welding position is usually preferred. In this position, the bead is least distorted by unsymmetrical pull of gravity, and loss of flux is minimized so that there is less need for using dams and restraints to keep the flux from spilling off the weld area.

When heavy assemblies that require fillet welds are difficult to manipulate into the flat welding position, the horizontal welding position (for fillet welds) may be used. To compensate for the lopsided flow of the filler metal in horizontal-position welding, the electrodes are spaced far enough apart to make separate weld puddles. The leading electrode deposits a layer that sags down to cover more of the flat surface than of the vertical surface. Trailing electrodes are angled to deposit most of the metal on the vertical wall of the joint. The composite of all the beads makes a relatively symmetrical fillet.

Submerged-arc welded bridge girders and other welded bridge structural components are designed and fabricated in accordance with code specifications (AWS D2.0) in order to attain prequalified status. Although welding in the flat position is generally preferred, the code states that fillet welds may be made in either the flat or horizontal position, except that the size of single-pass multiple-arc fillet welds made in the horizontal position shall not exceed ½ in. A change from flat to horizontal welding position in tandem-arc welding of girders is described in the following example.



Item	Single electrode, 1-in. stickout	Tandem electrodes, 1-in. stickout	Tandem electrodes, 5-in. stickout
Arc time, hr	8.6	4.6	2.8
Deposition rate, lb per hr	14	26	42

Side(a)	Pass(a)	Current, amp	Voltage	Welding speed, ipm
Submerged-Arc Welding With Single (1-In. Stickout) Electrode(a)				
1	First filler	400 to 450 (dcrp)	32 to 33	14 to 15
	Remaining	575 to 600 (dcrp)	33 to 34	13 to 14
2	1 to 3(b)	650 to 700 (dcrp)	35 to 38	12 to 14
Submerged-Arc Welding With Single (1-In. Stickout) and Tandem (1-In. Stickout) Electrodes(a)				
1	First filler (single electrode)	450 to 500 (dcrp)	32 to 34	17
	Remaining (leading electrode)	500 to 600 (dcrp)	34 to 36	15 to 16
	(trailing electrode)	475 to 550 (ac)	....	(tandem)
2	1 to 3 (single electrode)(b)	450 to 500 (dcrp)	32 to 34	10 to 12
Submerged-Arc Welding With Single (1-In. Stickout) and Tandem (5-In. Stickout) Electrodes(a)				
1	First filler (single electrode)	400 to 450 (dcrp)	33 to 35	20 to 21
	Second filler (leading electrode)	550 (dcrp)	35 to 38	19
	(trailing electrode)	500 (ac)	38 to 42	(tandem)
	Remaining (leading electrode)	650 (dcrp)	35 to 38	22
	(trailing electrode)	550 (ac)	38 to 42	(tandem)
2	1 to 2 (single electrode)(b)	700 to 725 (dcrp)	35 to 37	10 to 12

(a) Joint was sealed from side 1 by a root pass made by shielded metal-arc welding, using a ⅛-in.-diam E7018 electrode at 110 to 140 amp, 18 to 20 volts. Filler passes were made by submerged-arc welding, using 5⁄32-in.-diam EM12K electrode wire and F61 flux. Welding was done in the flat position. Power supplies were an 800-amp motor-generator for the single electrodes and for the leading tandem electrodes, and a 1000-amp transformer for the trailing tandem electrodes. Preheating consisted in heating the vessel to 175 F minimum. Postweld heating consisted in holding the vessel at 1150 F minimum for 2½ hr, then furnace cooling it to 600 F. (b) After air carbon-arc back gouging approximately ⅜ in. deep to reach sound metal.

Fig. 33. Pressure vessel with a 10-ft longitudinal seam for which welding time was progressively reduced by changing from automatic submerged-arc welding entirely with a single electrode to first-side welding of all but the first filler pass with tandem electrodes having a 1-in. stickout and then a 5-in. stickout (Example 66)

Example 67. Change in Welding Position That Increased Welding Efficiency and Reduced Handling of Tandem Welded Bridge Girders (Fig. 34)

Originally, I-beam bridge girders were welded in the flat position with the web tilted at 45°, as shown in Fig. 34(a), after assembly by tack welding. The welding head was held in a vertical position during travel along each joint, and the girder was progressively repositioned to make the four welds in the numerical sequence shown in Fig. 34(a). The wires in the two-electrode welding head, each fed by a separate wire-feed motor, were spaced 1 in. apart, so that both fed the same weld puddle, developing a single bead (Fig. 34b). Although sound welds were made with this procedure, production rate was limited because the girders had to be repositioned and aligned for each weld, and only one weld could be made at a time.

To increase the production rate, the girder was oriented so that two welds could be made simultaneously in the two horizontal positions shown in Fig. 34(c) and (d). For horizontal-position welding, the positions of the electrodes were changed so that the fillet welds would be of proper shape. First, the two electrode wires were spaced 4½ in. apart, so that the bead from the leading wire solidified before the second bead was deposited; welding thus became a multiple-pass operation. This was necessary because gravity pulled the molten metal toward the horizontal member of the girder and the proper shape for the weld bead could not be developed from a single weld puddle. In addition, the trailing electrodes were positioned as shown in Fig. 34(c) and (d), to develop the upper portion of the fillet welds. The two-layer weld deposits built up in these horizontal positions are shown in Fig. 34(e).

With the reduction in handling time from that required when one weld at a time was deposited in flat-position welding, and with the increase in deposition rate obtained with the "two-pass" welding effected by the use of spaced electrodes, the time for welding each girder was reduced 65% by welding in the horizontal position.

Welding conditions for various fillet sizes, using the flat position and horizontal position, are given in the table with Fig. 34.

Improvements in equipment and technique have made it possible to use three, and sometimes four, electrodes in the horizontal position, depending on fillet size and code requirements; the table with Fig. 34 lists welding conditions for 5⁄16 and 3⁄8-in. fillets, using three electrodes and the horizontal position, and for ½-in. fillets, using four electrodes and the horizontal position. All of the welding data in the table are applicable to a series of carbon steels and high-strength low-alloy steels covered by the specifications in AWS D2.0 — including ASTM steels A36, A441, A500 (grade B), and A588. Filler metals and flux-electrode combinations are selected for compatibility with the base metal, in accordance with specifications in AWS D2.0.

Cost of Tandem-Arc vs Single-Arc Welding. The example that follows discusses the use of single-arc and tandem-arc welding of girth joints between various thicknesses of plates that comprised the cylindrical shells of large field-erected storage tanks, and presents the results of a ten-year cost study made to determine which of the two methods was more economical in relation to specific plate thickness.

Example 68. Tandem-Arc vs Single-Arc Welding of Large Field-Erected Storage Tanks (Fig. 35)

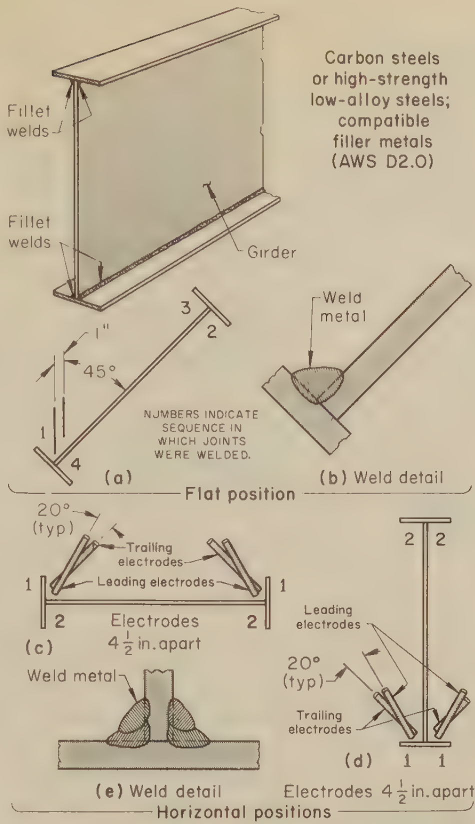
Cylindrical shells of large field-erected storage tanks were constructed by welding successive shell-ring courses, as shown schematically in Fig. 35. Although various processes were used for welding the vertical butt joints, the horizontal girth joints were submerged-arc welded, using either the single-arc or the tandem-arc method. Both methods employed a special traveling cab, containing the welding operator and the welding equipment, driven along the upper edge of a shell ring. Tandem-arc welding was limited to plates ½ in. or more in thickness, because the tandem equipment would deposit excess reinforcement with plates less than ½ in. thick.

Although the tanks were of various sizes, the one shown in Fig. 35 indicates typical construction. This tank, 180 ft in diameter and 48 ft high, had six shell-ring courses, with the thickest plate (1¼ in.) at the bottom and the thinnest (5⁄16 in.) at the top. The two joints at the top of the tank, between plates 5⁄16, 13⁄32, and 5⁄8 in. thick, were welded from both sides by the single-arc method (see detail A in Fig. 35). The three joints between the four lower courses of plates (5⁄8, 0.82, 11⁄32, and 1¼ in. thick, top to bottom) were welded from both sides by the tandem-arc method (joint design is shown in detail B in Fig. 35).

A comparison of labor and material costs for the use of single-arc and tandem-arc welding over a ten-year period for tanks up to 260 ft in diameter and 64 ft high, with shell courses ranging in thickness from 3⁄16 to 1½ in., is presented in the graph of Fig. 35. Labor costs were based on a labor-plus-overhead rate of $14 per hour. Material costs were based on a flux consumption of 1.7 pounds of flux per pound of weld metal deposited. The amounts of deposited metal and the material costs were the same for single-arc as for tandem-arc welding, for plates ranging in thickness up to 1⅛ in.

Summary of Cost-Comparison Data. On plate thicknesses of ½ to 1⅛ in., tandem-arc welding cost $0.55 to $0.43 less per foot than single-arc welding (the difference in labor cost). On plate more than 1⅛ in. thick, the per-foot cost of tandem-arc welding was $2.08 to $2.40 less for labor and $0.15 to $0.17 less for material, or $2.23 to $2.57 less for both items, depending on the plate thickness (see graph in Fig. 35).

The large increase in labor cost occurred because, for plate more than 1⅛ in. thick, a shielded metal-arc root pass was required before single-arc welding, to avoid cracking in the first submerged-arc weld bead.



Fillet size, in.	Electrode diam, in.(a)	Current, amp	Welding voltage	Travel speed, ipm
Flat Position, Two Electrodes (L and T) 1 In. Apart(b)				
¼	L, 3⁄16	715, dcsp	31-35	60
	T, 5⁄32	540, ac	31-35	
5⁄16	L, 3⁄16	800, dcsp	33-37	47
	T, 3⁄16	655, ac	33-37	
3⁄8	L, 3⁄16	800, dcsp	34-40	37
	T, 3⁄16	720, ac	38-44	
½	L, 3⁄16	1000, dcsp	34-40	27
	T, 3⁄16	855, ac	38-44	
5⁄8	L, 3⁄16	1000, dcsp	34-40	18
	T, 3⁄16	900, ac	38-44	
¾	L, 3⁄16	1000, dcsp	34-40	13
	T, 3⁄16	900, ac	38-44	
Horizontal Position, Two Electrodes (L and T) 4½ In. Apart(b)				
¼	L, 5⁄32	500, dcrp	28-30	40
	T, ⅛	400, ac	32-34	
5⁄16	L, 5⁄32	650, dcrp	32-34	32
	T, ⅛	500, ac	32-34	
3⁄8	L, 5⁄32	650, dcrp	32-34	26
	T, ⅛	500, ac	32-34	
Horizontal Position, Three Electrodes (L, T and T) 3 In. and ⅞ In. Apart(c)				
5⁄16	L, 5⁄32	600, dcrp	28-30	40
	T, ⅛	550, ac	32-34	
	T, 3⁄32	350, ac	27-29	
3⁄8	L, 5⁄32	650, dcrp	28-30	34
	T, ⅛	550, ac	32-34	
	T, 3⁄32	350, ac	27-29	
Horizontal Position, Four Electrodes (L, T, T and T) 3 In., ⅞ In., and 4 In. Apart(c)				
½	L, 5⁄32	750, dcrp	28-30	28
	T, ⅛	600, ac	32-34	
	T, ⅛	500, ac	30-32	
	T, 3⁄32	350, dcsp	27-29	

(a) L = leading electrode, T = trailing electrode. (b) As shown in illustration. (c) Not shown in illustration.

Because of decreased workhandling and increased deposition rate in horizontal-position welding, production time was reduced 65%. Techniques illustrated were used for girders of various lengths and section thicknesses. Table above gives conditions for single-pass tandem-arc deposition of different sizes of fillet welds in both welding positions.

Fig. 34. Tandem-electrode submerged-arc fillet welding of bridge girders in the flat and horizontal positions (Example 67)

Submerged-Arc Welding vs Other Arc Welding Processes

Submerged-arc welding often is selected in preference to other processes because it is faster. In the example that follows, submerged-arc welding was not as fast as flux-cored arc welding, one of several processes with which it was compared, but it was preferred on the basis of lower cost and other production advantages.

Example 69. Cost of Welding a Planetary-Gear Carrier by Submerged-Arc Welding vs Three Other Arc Welding Processes (Table 9)

The six 3⁄8-in. fillet welds that joined three spacers to the backing plate of a planetary-gear carrier (see illustration in Table 9) had to be free of particles that could flake off into system oil and clog oil holes and lines, and to have enough strength and notch toughness to withstand shocks of sudden load changes in service.

To evaluate suitability and costs, gear carriers were arc welded by four different processes — shielded metal-arc (with ¼-in. and 5⁄16-in. electrodes), gas metal-arc, flux-cored arc, and submerged-arc welding. All proved capable of providing welds that would satisfy service requirements. A time-and-cost comparison of the processes is presented in Table 9. As this comparison shows, flux-cored arc welding required the least welding time per assembly. Submerged-arc welding was the second-fastest process, as well as the least expensive. Unlike the three other processes, submerged-arc welding left no weld spatter to be cleaned off the workpiece (at additional expense). Accordingly, submerged-arc welding was adopted for regular production. No postheating was employed after any of the welding processes evaluated.

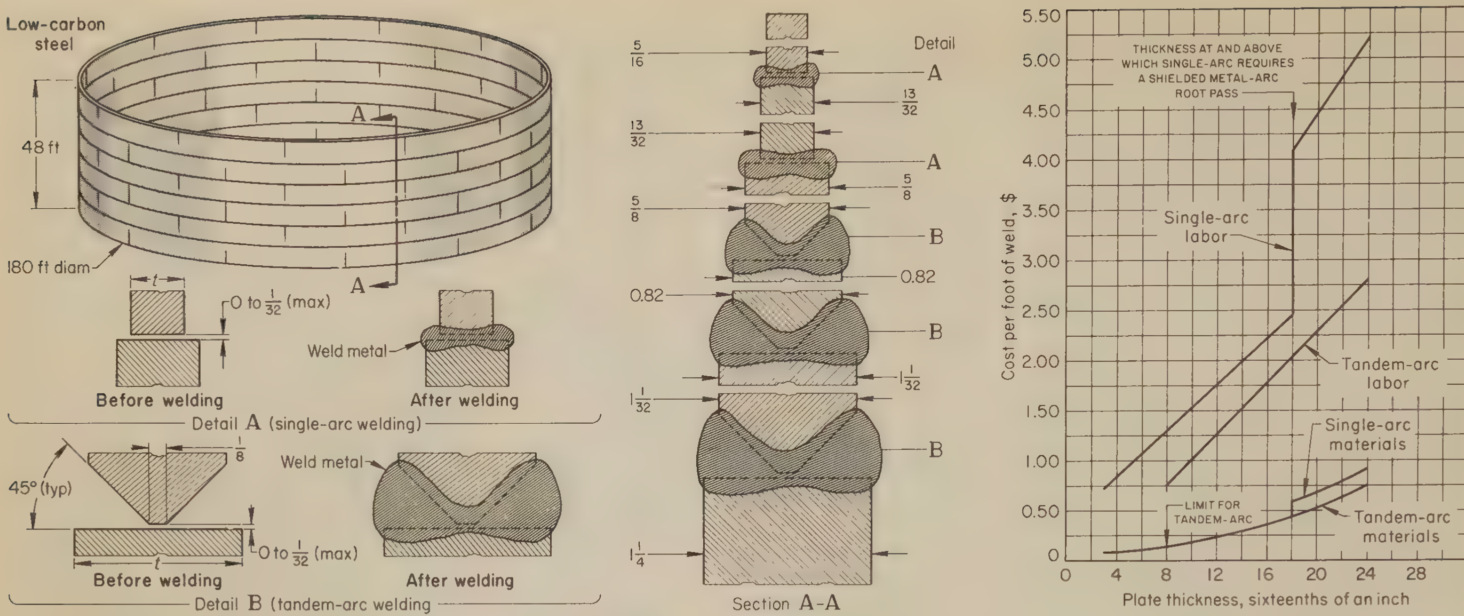
As shown in section A-A in the illustration in Table 9, the spacers overlapped the backing plate, and were welded to it by fillet welds on both sides of the joints. First, the assembly was loaded spacers-down into a positioner tilted at 45°; it was rotated to maintain flat position under the electrode throughout the deposition of each weld. After the welds on the lower sides of the joints had been completed, the assembly was reversed and reloaded into the positioner with the spacers up, and the welds on the upper sides were made.

Submerged-Arc Welding vs Shielded Metal-Arc Welding

Submerged-arc welding is faster than shielded metal-arc welding, because more current can be applied to the submerged arc and because it does not involve the interruptions or changes in speed that are characteristic of shielded metal-arc welding, and that impede steady production. The advantages can be realized in welding both large and small workpieces, as illustrated by the next five examples, in which the productivity of submerged-arc welding is compared with that of shielded metal-arc welding (see also Examples 58, 69 and 75, for similar applications).

Examples 70 to 74. Changes From Shielded Metal-Arc Welding to Submerged-Arc Welding That Increased Production

Example 70 — Collar-Ring Assembly (Fig. 36). The low-carbon steel collar-ring assembly shown in Fig. 36 was produced by fillet welding a roll-formed and welded cylinder to a gas-cut ring. The weld was required to have a good appearance. Originally, because production quantity was low, and it was desirable to keep investment in equip-



The joint design shown in detail A was used for single-arc welding of plates 3/16 to 7/16 in. thick. The joint design shown in detail B was used for tandem-arc welding of plates ½ to 1½ in. thick, and for single-arc welding of plates 7/16 to 1 in. thick. For single-arc welding of plates 1 to 1½ in. thick, the joint design shown in detail B was used, but with the 0-to-1/32-in. root opening increased to 3/16 in.

Fig. 35. Typical field-erected storage tank (upper left) in which horizontal girth joints between shell-course plates were butt welded by single-arc and tandem-arc methods, using the joint designs shown. Graph at right compares costs of the two methods for welding different plate thicknesses in the construction of various sizes of tanks over a ten-year period. (Example 68)

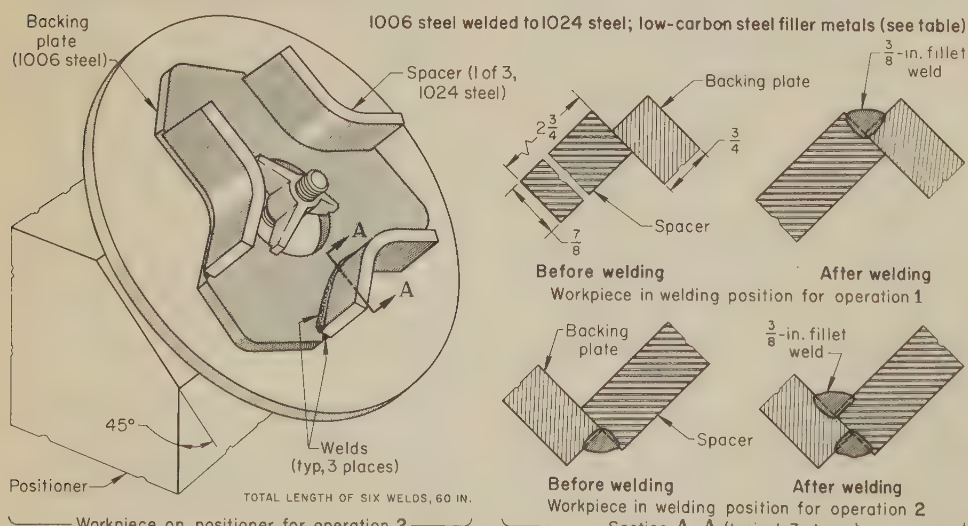
ment to a minimum, shielded metal-arc welding was used. For this welding process, the cylinder and ring were tack welded in four places, the assembly was inclined at 45° on a welding positioner, and the joint was welded in the flat position in three passes as the assembly was rotated. Time to produce one weldment was about 46 min.

When production demand increased, it was decided to replace shielded metal-arc welding by automatic submerged-arc welding. The submerged-arc welding head was modified by installing a switch in the wire-feed motor circuit, which enabled the operator to stop the electrode-wire drive before he turned off the generator, in order to prevent the electrode from sticking in the weld puddle at the end of the welding cycle. The assembly was tack welded and mounted on a fixture that allowed the assembly to be rotated on an axis at 45° from vertical, so that it could be welded in the flat position. Time required to produce one weldment was 16 min — about one-third the time required by the shielded metal-arc process.

Additional processing data for shielded metal-arc and submerged-arc welding of the collar-ring assembly are given in the table that accompanies Fig. 36.

Table 9. Times and Costs for Welding a Gear Carrier by Four Processes (Example 69) (a)

Item	Shielded metal-arc welding: 1/4-in. E7024 electrode	Shielded metal-arc welding: 5/16-in. E6013 electrode	Gas metal-arc welding; 1/16-in. E70S-5 electrode	Flux-cored arc welding; 3/32-in. E70T-2 electrode	Submerged-arc welding; 5/64-in. EM12K electrode
Current (dcrp), amp(b)	375	420	325	500	440
Deposition rate, lb per min	0.1900	0.1558	0.1950	0.3370	0.2667
Electrode cost per lb	$0.186	$0.145	$0.210	$0.290	$0.130
Flux cost per lb of electrode wire	...	...	...	...	$0.140(c)
Gas cost per lb of electrode wire	...	...	$0.04(d)	$0.01(e)	...
Materials cost per lb of metal deposited (including spatter loss)	$0.28	$0.22	$0.26	$0.36	$0.27
Welding time per piece, min	8.316	9.108	8.217	4.752	5.791
Welding materials cost per piece	$0.392	$0.308	$0.364	$0.504	$0.378
Total cost, materials and labor	$1.05	$1.05	$0.90	$0.85	$0.80



(a) Length of welds, 60 in.; fillet size, ⅜ in.; volume per inch of weld, 0.0825 cu in. Both manual and semiautomatic processes were employed. (b) Settings were based on attaining equal quality of weld. (c) Flux (F71) cost for depositing 1 lb of weld metal was $0.197. (d) 60% argon – 40% carbon dioxide, at 30-35 cfh. (e) Carbon dioxide, at 30-35 cfh.

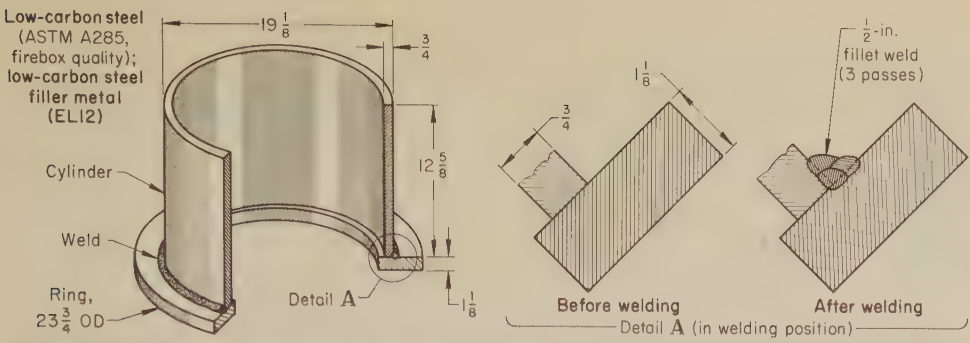
Example 71 — Steam-Boiler Header (Fig. 37). In welding radial stub tubes to a steam-boiler header (see Fig. 37), production rate using automatic submerged-arc welding was 2¾ times that obtained by shielded metal-arc welding. For both methods, stub tubes were held in place for welding by two tack welds 180° apart, made manually. When the shielded metal-arc process was used, the operator welded 180° on all stub tubes while standing on one side of the header; after removing the slag, he completed the welds from the other side of the header.

Submerged-arc welding was done by a rotating welding head that was supported by an overhead-trolley crane. The welding head was located by a pin that was inserted into the stub tube before welding was begun. The arc was started, and the four beads shown in Fig. 37 were deposited without stopping. Unfused flux was removed continuously by a vacuum hose attached to the welding head, and slag was removed manually by the operator.

Additional welding details are given in the table that accompanies Fig. 37.

Example 72 — Large Piston (Fig. 38). The large hydraulic-jack piston shown in Fig. 38 was assembled by welding three low-carbon steel castings (head, piston body, and seat) at girth joints. When similar smaller pistons with wall thicknesses of 3 to 5 in. had been assembled by shielded metal-arc welding, about one welded joint in eight was found to be defective and had to be reworked.

Because of the experience with the pistons with 3 to 5-in. wall, it was decided to use submerged-arc welding to assemble four large pistons, in which an 8-in. wall was to be joined to a 6⅝-in. wall, using the joint design shown in detail A in Fig. 38. The

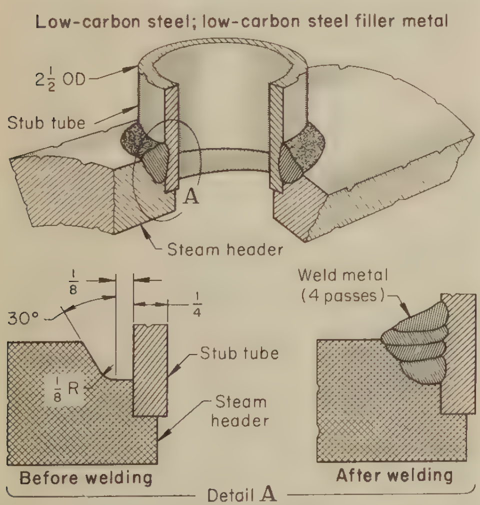


Item	Shielded metal-arc welding	Submerged-arc welding
Joint type	Circumferential corner	Circumferential corner
Weld type	Fillet	Fillet
Joint preparation	Edge sheared square	Edge sheared square
Power supply	500-amp transformer	600-amp motor-generator
Electrode wire	¼-in. E7024	3/32-in.-diam EL12
Flux	....	F62
Fixture	500-lb positioner	500-lb positioner
Voltage, v	Not measured	32
Current, amp	375 (ac)	425 (dc)
Welding position	Flat	Flat
Wire feed	Manual	Automatic
Wire-feed rate, ipm	10	140
Welding speed, ipm	11	20
Number of passes	Three	Three
Welding time per assembly, minutes	46(a)	16(b)

(a) Includes 4 min for setup, 3 min for cleaning. (b) Includes 5 min for setup; no cleaning needed.

Fig. 36. Collar-ring assembly for which production rate was tripled when submerged-arc welding replaced shielded metal-arc welding (Example 70)

outside surfaces of the three castings to be welded were rough machined and the joints were prepared by machining. The joints were of the interlocking type (see detail A in Fig. 38), and provided support for the unwelded components during positioning on variable-speed welding rolls. Joint areas were preheated to 400 F with gas torches as the piston was rotated. The welds were made in 380 passes, and were produced oversize and machined to size after



Automatic Submerged-Arc Welding

Joint type	Corner
Weld type	Single-J-groove
Electrode wire	0.045-in.-diam low-carbon steel(a)
Current	200 to 250 amp, dcrp(b)
Voltage	30 v
Welding speed	6 ipm
Welding position	Horizontal
Number of passes	Four

(a) A 5/32-in. E7018 electrode was used for shielded metal-arc welding. (b) Supplied by a 300-amp constant-voltage rectifier. Current for shielded metal-arc welding was 195 amp, supplied by a 300-amp constant-current rectifier.

Fig. 37. Steam-boiler header for which production using automatic submerged-arc welding was 2¾ times that for shielded metal-arc welding (Example 71)

magnetic-particle inspection and stress relief. The welded pistons were stress relieved at 1115 F for 7 hr and furnace cooled to 600 F. They were then machined to the size required for application of a bronze overlay (see Example 93, in the article on Gas Metal-Arc Welding, for a description of this surfacing operation). Each welded joint was ultrasonically inspected for a distance of 3 in. on each side of the weld. After inspection, the pistons were hydrostatically tested at 3000 psi. There were no rejections. Additional welding data are given in the table with Fig. 38.

Production time for welding the large piston was 101 hr, which was a considerable improvement over the production time of 212 hr for the smaller pistons assembled by shielded metal-arc welding.

Example 73 — Press-Gear Blank (Fig. 39). The blank for a large press gear was made by welding a forged medium-carbon steel rim to a web and crank arm made of low-carbon steel plate, as shown in Fig. 39. Semiautomatic submerged-arc welding was used (under the conditions given in the table with Fig. 39), because the production lot for any one size was too small to justify the cost of more expensive equipment for automatic welding.

Before welding, the web and crank arm were cut to shape with an oxy-natural gas torch, guided by a template, and the crank arm was beveled (by gas cutting) to make the groove shown in detail B of Fig. 39. The rim, web and crank arm were positioned for welding, and the rim was preheated by torch to 150 F. With the exception of the one groove weld shown in Fig. 39, detail B, the welds were fillet welds.

Depending on the size of the blank, the production time varied from 5 to 8 hr per piece. This was 50 to 70% faster than the rate obtainable using shielded metal-arc welding (with low-hydrogen electrodes).

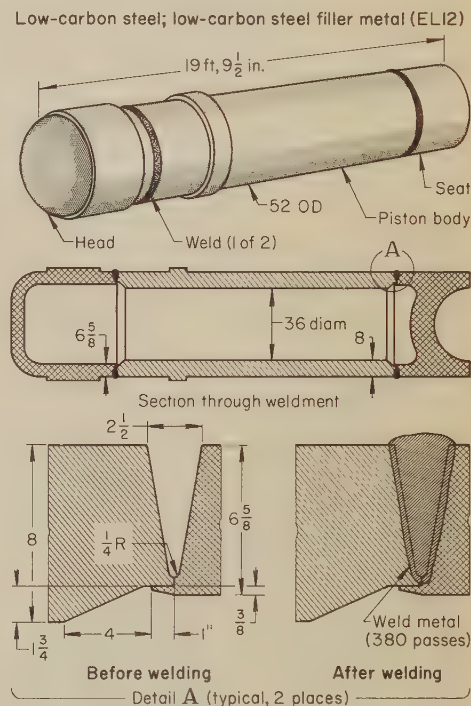
Example 74 — Double-Wall Bearing Mold (Fig. 40). The joint between the sleeve and the shell in the low-carbon steel bearing mold shown in Fig. 40 was welded originally by the shielded metal-arc process. The sleeve was positioned in the bearing shell by use of fixtures and its flange was tack welded in four places. The fixtures were then removed, and the joint was shielded metal-arc welded. To meet production requirements, six welders were needed.

When automatic submerged-arc welding replaced shielded metal-arc welding, one operator and one machine produced as many molds as had previously been produced by six welders, and operators that had less basic knowledge of welding could be assigned to the job.

For automatic submerged-arc welding, the sleeve was positioned on the shell on a rotating variable-speed turntable; distortion during welding was prevented by an overarm rotating-disk hold-down. The welding operation was conventional. Electrode wire was fed to the welding head from a 25-lb coil mounted in an overhead spool holder, and flux was fed from an overhead hopper. A contoured flux-retaining shoe placed on the outside of the shell, at the top edge, ensured provision of a protective layer of granular flux for the weld puddle. Excess flux was picked up by vacuum and, after screening, was returned to the overhead hopper.

Bearing molds of various sizes were made. When the shell of a mold was ¼ in. thick or less, automatic submerged-arc welding was not practical and gas tungsten-arc welding was used (see Example 129 in the article on Gas Tungsten-Arc Welding).

A comparison of welding conditions for shielded metal-arc and submerged-arc



Conditions for Submerged-Arc Welding

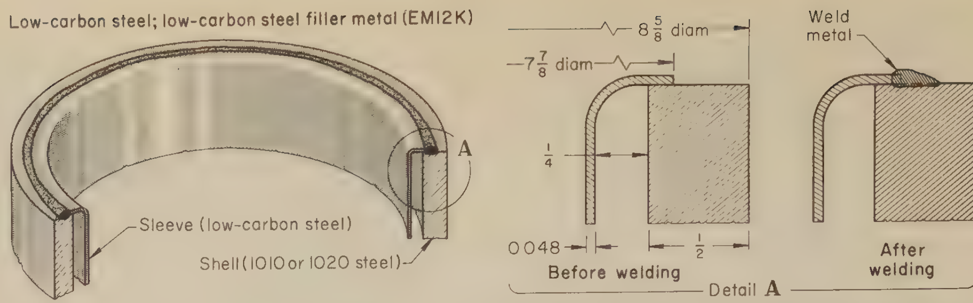
Joint type	Circumferential butt
Weld type	Single-U-groove, integral backing
Joint preparation	Machining
Power supply	1000-amp transformer
Wire feed	Fully automatic, constant speed
Welding head	Machine held, air cooled
Fixture	50-ton variable-speed roll
Auxiliary equipment	Exhaust fan, vacuum flux remover, positioning arm
Electrode wire	5/32-in.-diam EL12(a)
Flux	F71(a)
Welding position	Flat (horizontal-rolled pipe position)
Number of passes	380
Current and voltage:	
Passes 1 through 3	700 amp, ac; 38 v
Remaining passes	750 amp, ac; 40 v
Preheat	400 F (by torch)
Postheat (stress relief)	7 hr at 1115 F; furnace cool to 600 F
Welding speed	9½ ipm

(a) Electrode and flux yielded a weld deposit containing 0.12 C, 0.84 Mn, 0.72 Si, 0.018 S.

Fig. 38. Large piston assembled by submerged-arc welding. Production time was 101 hr, but production time for similar smaller pistons assembled by shielded metal-arc welding was 212 hr. (Example 72)

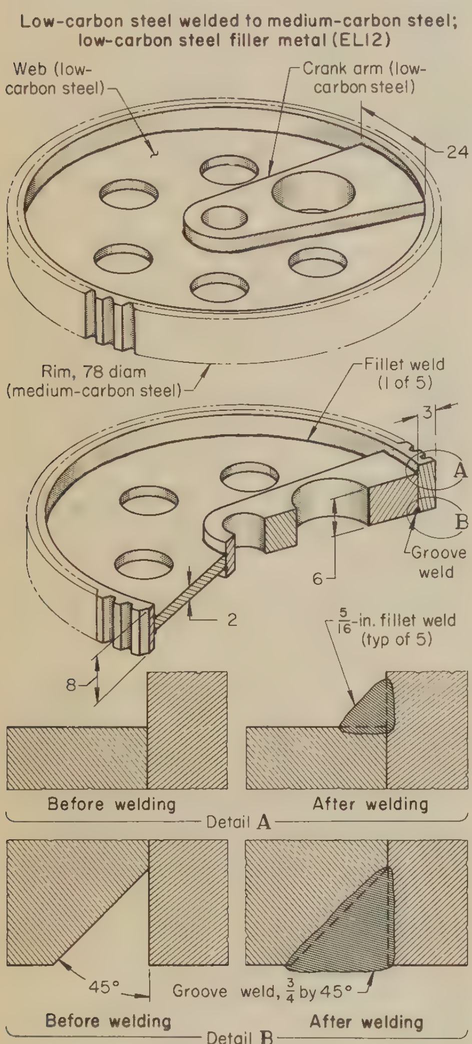
welding of the bearing molds is given in the table that accompanies Fig. 40.

In some applications, the uniformity and freedom from spatter of submerged-arc welds, as compared with shielded metal-arc welds, can reduce or eliminate postweld finishing requirements. In the example that follows, changing to submerged-arc welding eliminated the need for grinding the weld, and gave increased welding speed and freedom from distortion and leaks. In addition, the greater welding speed and weld uniformity enabled the welding of joints having different curvatures.



Item	Shielded metal-arc	Automatic submerged-arc
Joint type	Lap	Lap
Weld type	Fillet	Fillet
Power supply	400-amp rectifier	400-amp rectifier
Electrode wire	⅛-in.-diam E6013	$\frac{3}{32}$-in.-diam EM12K
Flux	....	F61
Welding position	Flat	Flat
Number of passes	One	One
Current, amp	105 to 125, dcsp	240 to 300, dcsp
Voltage, v	12 to 20	18 to 25
Welding speed, ipm	5 to 7	60 to 65
Preheat	None	None
Production time per piece, min	10 to 12	2

Fig. 40. Double-wall bearing mold that was welded by the submerged-arc process at six times the production rate obtained in shielded metal-arc welding (Example 74)



Semiautomatic Submerged-Arc Welding

Joint types	T; corner
Weld types	Fillet; single-bevel-groove
Power supply	28 to 40-v, 400 to 600-amp, constant-voltage motor-generator
Electrode wire	$\frac{5}{64}$-in.-diam EL12
Flux	F71
Current	400 amp, dcrp
Voltage	28 v
Number of passes	One
Deposition rate	15 to 20 lb per hour
Preheat	150 F(a)
Postheat (stress relief)	3 hr at 1175 F
Electrode consumption	15 lb per hour
Flux consumption	15 lb per hour
Welding speed	14 to 16 ipm
Production time	5 to 8 hr per blank(b)

(a) The rim only was preheated by torch. (b) Depending on size of gear blank.

Fig. 39. A typical press-gear blank that was made 50 to 70% faster by semiautomatic submerged-arc welding than by shielded metal-arc welding (Example 73)

Example 75. Change From Shielded Metal-Arc to Submerged-Arc Welding of a Hydraulic Cylinder (Fig. 41)

The hydraulic cylinder shown in Fig. 41 was produced by welding two spuds (1117 steel) and an end plug (1020 steel casting) containing a mounting eye to a cylinder (1015 steel). The joints at the spuds had to contain hydraulic pressure without leaking, and the joint at the end plug had to contain hydraulic pressure and also withstand the stresses developed during operation of the cylinder.

Originally, the joints were welded by the shielded metal-arc process, but production was slow and extensive grinding was necessary to remove unwanted weld metal. When standard spuds with flat ends were used, an exceptionally high level of welder skill was needed to produce good assemblies. If the bases of the spuds were machined for good joint fit-up, a better weld was obtained, but because the outside diameters of the cylinders ranged from 3 to 6 in., it was necessary to machine the same radii in the spuds, which then had to be classified and stored according to radius.

With the increased depth of fusion provided by submerged-arc welding, joint fit-up was adequate when spuds with a mean-radius contour on the base were used. Maximum misfits of the mean-radius contour are shown in Fig. 41, section A-A, submerged-arc welding. An improved design was developed for the cylinder-to-plug joint, as shown in Fig. 41, detail B. This provided a flat bottom for the weld groove and positive location of the plug on the cylinder; as a result, welds were more uniform and had fewer flaws and leaks than those made with the original design.

To weld the spuds (section A-A in Fig. 41), the cylinder was positioned on its side, spuds up, and the electrode, mounted on a rotating head, revolved 360° to make the weld. To make the cylinder-to-plug weld, shown in detail B in Fig. 41, the electrode was held stationary and the cylinder assembly was rotated under it. Times for attaching spuds and end plug and finish grinding of welds are given in the table with Fig. 41.

The cost of welding, per assembly (labor plus overhead), was reduced from $1.52 for shielded metal-arc welding to $0.57 for submerged-arc welding. In addition, electrode cost was reduced for submerged-arc welding, by eliminating loss from discard of short electrodes and ends of electrodes, and loss from spoilage by moisture absorption. The uniformity, appearance, and quality of the welds were improved, and there was better, and more even, penetration, and less distortion. Rework after leak testing was reduced from over 5% to less than 1%.

Welding conditions for the two processes are given in the table with Fig. 41.

Submerged-Arc Welding vs Casting

Weldments are sometimes used instead of castings to obtain improved quality or increased production. The example that follows describes an application in which a submerged-arc welded assembly replaced a casting when production requirements for the casting exceeded the capacity of the foundry.

Example 76. Submerged-Arc Welding of Brake Shoes Previously Produced as Castings (Fig. 42)

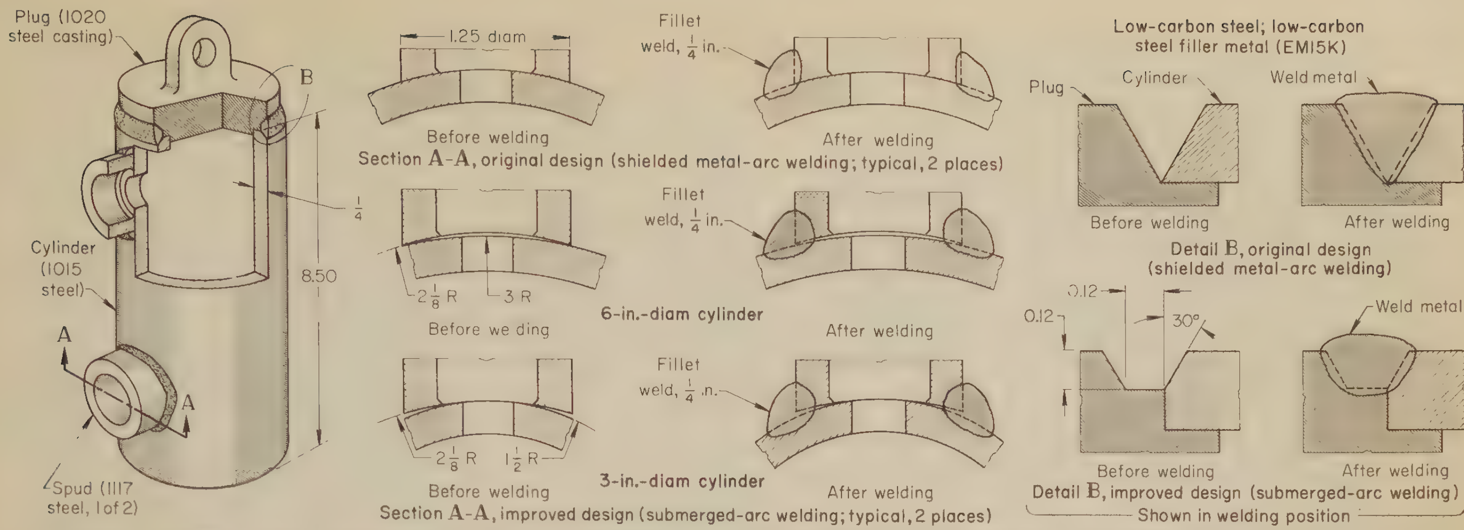
Originally, brake shoes like the one shown in Fig. 42 had been produced as castings, but when production requirements became more than the foundry could handle, they were produced as weldments. The welded assembly consisted of a web of 1035 steel bar and a table of 1010 steel plate. Both bar and plate were press formed to the curvature required, but springback of the formed sections caused difficulty in welding. The difficulty was overcome by assembling the parts in a hydraulic press and tack welding them together. Shoes with braking surfaces 4 to 10 in. wide were made in this way. The shoe shown in Fig. 42 has a braking surface 8 in. wide.

Special submerged-arc welding equipment was built to produce the two 25¼-in.-long ¼-in. fillet welds (one on each side of the web) simultaneously. The electrode holders were mounted on retractable arms and were stationary during the welding cycle. The workpiece was placed on a welding table that was curved to fit the part and that was moved by a rack-and-pinion drive. Welding details are given in the table that accompanies Fig. 42.

The components were degreased and washed before welding. After welding, the assembly was stress relieved at 1300 F for 1 hr to temper the heat-affected zone on the web and to stabilize the structure. After stress relieving, the shoe was sized in a 1700-ton mechanical press.

Welding costs per assembly are given in the table that accompanies Fig. 42.

In the next example, gear blanks that had formerly been cast were fabricated by submerged-arc welding to eliminate defects that had resulted in high rework charges and scrap losses.



Item	Shielded metal-arc	Submerged-arc
Welding Conditions		
Power supply	Rectifier	Rectifier
Electrode wire	7/32-in.-diam E7024	3/32-in.-diam EM15K
Flux	....	F70
Current and voltage, spuds	180 amp, dcsp; 27 v	360 to 375 amp, dcsp; 29 v
Current and voltage, plug	180 amp, dcsp; 27 v	380 amp, dcsp; 27 v
Welding speed, spuds	5 ipm	20½ ipm
Welding speed, plug	6 ipm	6½ ipm
Number of passes	One	One
Electrode stickout	....	1 in.

Item	Shielded metal-arc	Submerged-arc
Labor Time per Assembly, Hr		
Welding two spuds	0.0675	0.0366
Grinding welds	0.0136	....
Welding one plug	0.0469	0.0267
Grinding weld	0.0411	....
Total, hr	0.1691	0.0633
Cost per Assembly		
Labor and overhead	$1.522	$0.57

Fig. 41. Hydraulic-cylinder assembly for which change from shielded metal-arc welding to submerged-arc welding resulted in better joints at approximately one-third the labor time and cost (Example 75)

Example 77. Submerged-Arc Welding Large Bull-Gear Blanks Formerly Produced as Castings (Fig. 43)

A large bull gear for a steel-mill drive was machined from the welded blank shown in Fig. 43. Blanks had formerly been sand cast in alloy steel, but too many castings had contained defects, such as cracks, porosity and shrink cavities, that were found only during the final stages of machining, after thousands of dollars of machining time had been expended.

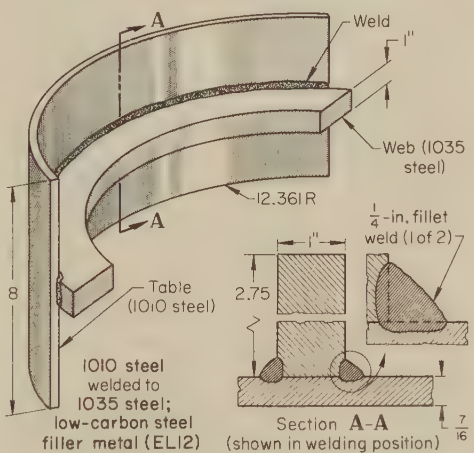
The welded blank was made up of the following components: a 4140 steel rim, which had been produced as a roll forging and rough machined; a hub, which had been gas cut from a 14-in.-thick slab of carbon steel (ASTM A36) and then rough machined on the outside diameter; 16 stiffeners, which had been sheared or gas cut from 1-by-3-in. 1020 steel bar stock, with one edge ground to facilitate fit-up; and a web, which had been gas cut from 2-in.-thick carbon steel (ASTM A36) plate. Double J-grooves were machined into the edges of the web where it was to be joined to the hub and the rim.

The sequence of operations for welding the bull-gear blanks was as follows:

A Tack weld.
1 Fit and tack web to hub.
2 Fit and tack web to rim (rim was preheated before welding).

B Join hub to web by automatic submerged-arc welding (see table with Fig. 43).
3 Preheat hub to 300 F.
4 Weld joint on side A half full (operation 1, detail E, Fig. 43).
5 Turn workpiece over and back gouge to sound metal.
6 Weld joint on side B full (operation 2, detail E, Fig. 43).
7 Turn workpiece over; complete weld on side A (operation 3, detail E, Fig. 43).

C Join rim to web, using shielded metal-arc welding for root passes and submerged-arc welding for filler passes (see table, Fig. 43).
8 Preheat the rim locally to 400 F.
9 Weld root pass on side A by shielded metal-arc welding (operation 4, detail F, Fig. 43).
10 Inspect root pass on side A (magnetic-particle inspection).
11 Weld joint on side A half full (operation 5, detail F, Fig. 43); follow with magnetic-particle inspection.



Conditions for Submerged-Arc Welding(a)

Joint type	T
Weld type	Double fillet
Power supplies (2)	Drooping-voltage, 40-v, 500-amp motor-generators
Welding heads (2)	600-amp, air cooled
Electrode wire	3/32-in.-diam EL12
Flux	F70
Welding position	Horizontal
Current	410 amp, dcrp
Voltage	23 v
Electrode stickout	1½ in.
Welding speed	14 ipm
Flux consumption	0.2 lb per ft
Number of passes	One
Preheat	None
Postheat (stress relief)	1 hr at 1300 F
Production rate	14 assemblies per hour
Production per month	500 assemblies

Welding Costs per Assembly

Electrode wire	$0.075
Flux	0.104
Labor and burden	1.130
Total	$1.309

(a) Welds were made simultaneously, using two welding heads.

Fig. 42. Brake shoe produced as a weldment instead of a casting, when demand exceeded foundry capacity (Example 76)

12 Turn the workpiece over and back gouge to sound metal.
13 Weld root pass on side B by shielded metal-arc welding (operation 6, detail F, Fig. 43).
14 Inspect root pass on side B (magnetic-particle inspection).
15 Weld side B half full (operation 7, detail F, Fig. 43); magnetic-particle inspect.
16 Weld side B full (operation 8, detail F, Fig. 43); magnetic-particle inspect.
17 Turn workpiece over; complete weld on side A (operation 9, detail F, Fig. 43); magnetic-particle inspect.

D Fit, tack and weld stiffeners to web, using flux-cored arc welding (see section B-B, Fig. 43, and the table with Fig. 43).

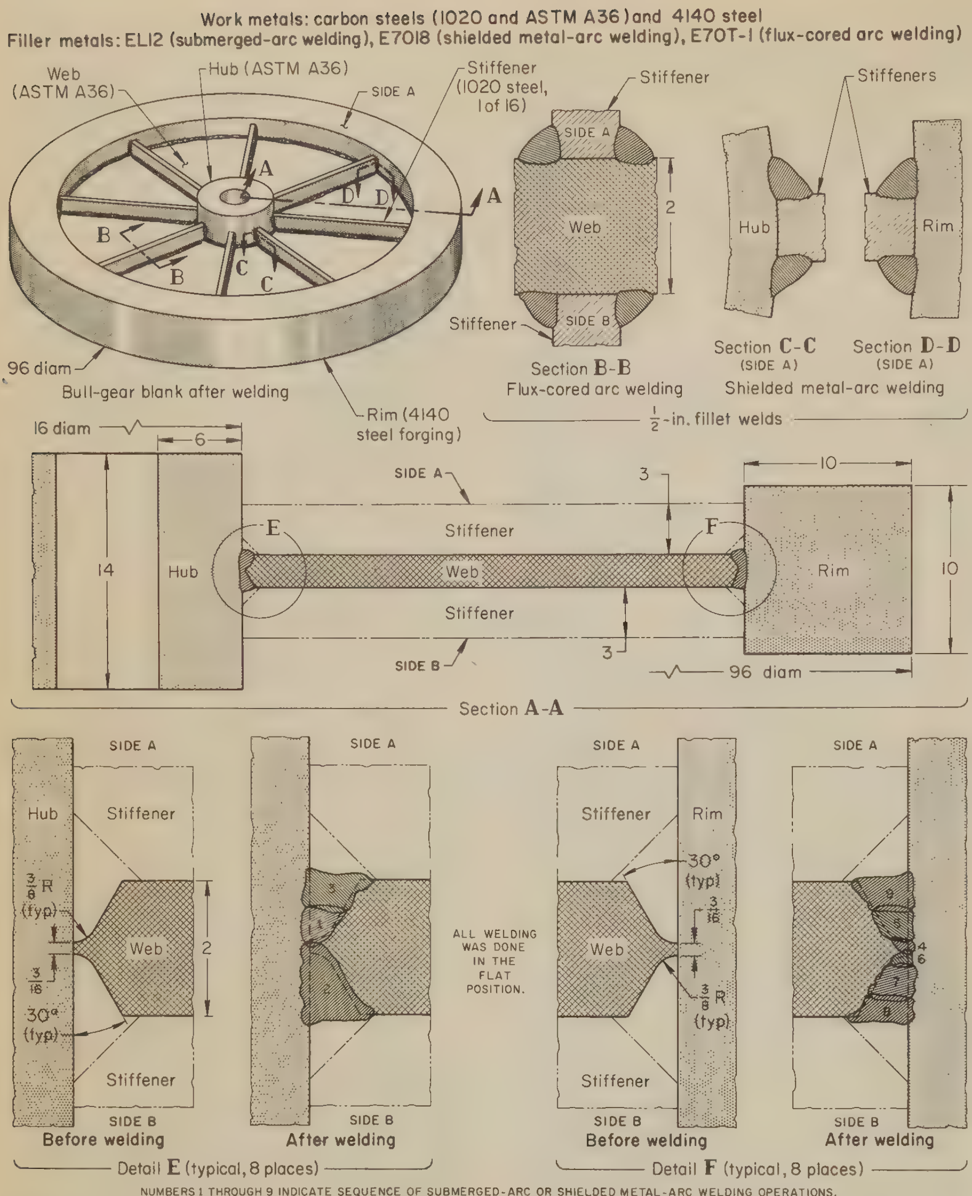
E Fit, tack and weld stiffeners to hub and rim, using shielded metal-arc welding (see sections C-C and D-D, Fig. 43, and the table that accompanies Fig. 43). Rim was preheated locally to 400 F.

The welded blank was covered with asbestos blankets, allowed to cool slowly, and then stress relieved at 1050 F for 6 hr. After cooling, the hub and rim joints were 100% ultrasonically inspected.

Welded gear blanks cost $1000 each to produce, exclusive of material cost. Cast blanks cost the same when only one or two were made from a pattern, but if six or more blanks of the same design were produced, the cost was less. The quality of the welded blanks was higher than that of the cast blanks, and no partly machined gears had to be discarded because of defects.

Safety

Submerged-arc welding presents many hazards that differ from those found in other arc welding processes, and that thus call for different precautions. There are, however, many areas where the same precautions may be required; among these are (a) care in selecting power supplies and auxiliary equipment of adequate capacity to provide the high current at the high duty cycles required by most submerged-arc welding installations; and (b) the installation, maintenance and operation of the equipment in accordance with safety



Welding condition	Submerged-arc(a)	Shielded metal-arc(b)	Flux-cored arc(c)
Power supply	40-v, 1200-amp rectifier(d)	400-amp rectifier	40-v, 500-amp rectifier(d)
Electrode wire	1/8-in.-diam EL12	3/16-in.-diam E7018	1/8-in.-diam E70T-1
Shielding gas	...	...	Carbon dioxide
Flux	F72	...	...
Current (dcrp), amp	380 to 420	160	450
Voltage, v	30 to 32	25	30 to 32
Welding speed, ipm	16 to 24	...	12 to 14
Preheat temperature, rim	450 F	400 F	450 F
Preheat temperature, hub	300 F	...	...

NOTE: After welding, the gear blank was stress relieved at 1050 F for 6 hr.

(a) Used for all welding operations in joining the web to the hub (operations 1, 2 and 3; see detail E), and for filler passes in joining the web to the rim (operations 5, 7, 8 and 9; see detail F). (b) Used for root passes in joining the web to the rim (operations 4 and 6; see detail F), and for tacking and welding stiffeners to hub and rim (sections C-C and D-D). (c) Used for joining stiffeners to web (section B-B). (d) Constant-voltage type.

Fig. 43. Bull-gear blank that was welded by automatic submerged-arc, shielded metal-arc, and semiautomatic flux-cored arc welding to improve quality and reduce costs (Example 77)

standards and codes (see the list of references presented at the bottom of column three on this page).

Certain parts of the equipment used in submerged-arc welding that are exposed to contact by the operator are at the welding-voltage potential. Although these parts are never at a higher potential than the open-circuit voltage (which should be kept as low as possible consistent with satisfactory welding, but in any case does not exceed 100 volts), there are circumstances under which low voltage can cause serious injury when the resistance of the electrical path through the body is low. One example is when the skin of a person is wet (as from perspiration) and when the person's body is in contact with the ground or a grounded steel plate. In addition, other injuries can be caused by the uncontrolled physical reaction that results from an electric shock. Every welding operator should know which parts of the equipment are at welding-voltage potential, and electric shock should be avoided by the observance of the following safe practices:

1. When the welding-current switch is closed (on), never touch any of the parts of the equipment that will be at the welding voltage or the open-circuit voltage. Typical of such parts are connectors, electrode wire, contact jaw or nozzle assembly, wire-reel frames and supports, electrode-wire feed rolls and pressure rolls, gear housings, and motor frames.
2. When the machine is not welding, when the operator leaves his work, or when the machine is to be moved, the contactor switch should be open (off). Equipment should be disconnected from power supply when not in use.
3. All control and switch boxes should be effectively grounded, and a separate lead should be used for grounding the frame of the carriage.

Helmets or hand shields are not normally necessary in submerged-arc welding, because the flux completely covers the end of the electrode and the welding zone. To avoid harmful exposure, however, accidental striking of the arc should be prevented by observance of the following precautions:

1. Never use the "inching" button control when the welding-current contactor is closed, because an arc may be created if the electrode wire accidentally touches the work.
2. The electrode wire and contact point on the work should be covered with flux before starting a weld, because the wire might melt off rapidly and create an arc across the open space if it is not completely covered.
3. The path of travel of the welding machine should be clear, because a short circuit and arcing will result if a part of the machine at welding voltage or open-circuit voltage touches a grounded object, such as a steel building-support member.

Safety goggles should be worn to protect the eyes from flying objects; the goggles may be tinted for protection against flashes of light from adjacent arc welding operations.

Handling of granular flux sometimes creates a dust in the atmosphere; and during welding, fumes and gases are produced. These dusts, fumes and gases may be hazardous, and so adequate ventilation should be provided.

The following references present detailed information on hazards and safe practices in submerged-arc welding:

"Safety in Welding and Cutting", ANS Z49.1, American National Standards Institute, Inc., 1430 Broadway, New York, N.Y. 10018 [Standards for: application, installation and operation of arc welding equipment; fire prevention and protection; personnel protection; health protection; ventilation. Includes a summary of industrial applications and a bibliography.]

"Safe Practices in Welding and Cutting", Chapter 9 in Section 1 of AWS "Welding Handbook", 6th Ed., American Welding Society, 345 East 47th St., New York, N.Y. 10017. [Discusses precautions in selection, installation and handling of arc welding equipment; fire prevention; eye and face protection; respiratory protection, including ventilation; protective clothing; protection against electric shock. Bibliography.]

"How to Do Submerged-Arc Welding", Bulletin 51-201A, Chapter 2, Linde Div., Union Carbide Corp., 270 Park Ave., New York, N.Y. 10017. [Outlines precautions and safe practices for submerged-arc welding.]

APPENDIX

Submerged-Arc Welding Fluxes and Relations Among Process Variables

By CLARENCE E. JACKSON*

SUBMERGED-ARC welding fluxes are produced in three forms: prefused, bonded, and agglomerated.

Prefused Fluxes. In the production of a prefused flux, the ingredients are dry mixed and then are melted in an electric furnace, by heat generated by passing large currents through the molten bath, rather than by the use of open arcs on the surface of the melt. The current can be regulated by changing the depth of immersion of the electrodes in the molten bath. After last-minute additions, the molten flux may either be water shotted or poured on chill plates to await crushing and sizing. Typical melting and pouring temperatures are between 2700 and 3100 F (1500 and 1700 C). With proper chilling, a glassy product is obtained (Fig. 44a). The product is passed over a series of screens that set upper and lower limits on the particle size — for example, through 12 mesh (0.055 in.) and on 200 mesh (0.0029 in.).

Advantages of prefused fluxes are:

1. They have extremely good chemical homogeneity.
2. Fines can be removed without changing the composition of the flux.
3. The product is not hygroscopic, thus simplifying storage problems.
4. Unfused portions can be reused several times without significant change in particle size or flux composition.
5. They are suitable for the highest travel speeds in welding operations.

The primary disadvantage of prefused fluxes is that deoxidizers and ferroalloys cannot be added to them without segregation or prohibitive losses during processing, because of the high temperatures involved.

Bonded Fluxes. In the production of a bonded flux, the raw materials are ground to approximately 100×D; they are dry mixed and then bonded together with an addition of potassium silicate or sodium silicate. The resulting mixture is pelletized, dried at a relatively low temperature, broken up by mechanical means, and screened (Fig. 44b).

Advantages of bonded fluxes are:

1. Because of the low temperatures involved in the bonding process, metallic deoxidizers and ferroalloys can be included in the flux.
2. The density of the flux is lower, which permits use of a thicker layer of flux in the weld zone.
3. The solidified slag is readily detachable after welding.

One disadvantage of a bonded flux is that fines cannot be removed without some alteration in the flux composition. Another disadvantage is that bonded fluxes are likely to absorb moisture.

Agglomerated fluxes are similar to bonded fluxes except that a ceramic binder is used. The high curing temperature of the binder (2550 F, or 1400 C) limits the use of deoxidizers and ferroalloys, as with fused fluxes.

Sizing of a submerged-arc welding flux is important because the size of the particles and the distribution of particle sizes determine the level of welding current at which a flux performs best. For currents greater than 1500 amp, the percentage of small particles must be increased, and that of coarser particles must be decreased. For bonded fluxes that are to be used at lower currents, sizing is less critical; these fluxes generally are available in only one sizing — for example, 12 × 150. The maximum welding current at which bonded fluxes can be used is generally 800 to 1000 amp. Some prefused fluxes of the modified calcium silicate type can be used at more than 2000 amp.

Table 10. Typical Compositions of Manganese Silicate Fluxes for Submerged-Arc Welding

Substance	Prefused flux	Bonded flux
MnO	42.0%	36.5%
MnO_2	...	5.2(a)
SiO_2	45.0	38.0
CaF_2	6.9	3.9
CaO	1.2	0.8
MgO	0.3	2.7
BaO	0.1	0.3
Al_2O_3	2.0	1.1
FeO	1.5	...
Fe_2O_3	...	2.7
TiO_2	0.1	0.1
K_2O	0.4	...
Na_2O	0.4	1.5
PbO	0.1	0.1
FeSi (50%)	...	7.1(b)
Ratio MnO/SiO_2	$\frac{42.0}{45.0} = 0.93$	$\frac{40.7}{45.6} = 0.89$

(a) At welding temperatures, MnO_2 reacts with silicon in ferrosilicon to yield additional MnO equal to 4.2% of the total flux (0.815 × 5.2% = 4.2%). (b) In reaction with MnO_2 at welding temperatures, silicon in ferrosilicon forms additional SiO_2 equal to 7.6% of the total flux (2.14 × 7.1% ÷ 2 = 7.6%).

Composition of Fluxes

In the development of the submerged-arc welding process in the middle 1930's, prefused fluxes consisting of complex silicates were used. The formulations were chiefly alumina silicates of manganese, calcium and magnesium. Manganese silicate compositions corresponding to the typical analyses shown in Table 10 have been used throughout the world. Composition is balanced using the MnO-SiO_2 phase diagram (Fig. 45; Ref 1) as a guide to melting range and structure. With a bonded flux, fusion is accomplished during the welding operation, and the final reaction between molten flux and weld metal is similar to that with prefused flux.

As explained in the footnotes in Table 10, the ferrosilicon in a bonded flux reacts in the weld zone with the manganese dioxide to generate additional manganous oxide and silica. In this manner, a ratio of MnO to SiO_2 that is suitable for submerged-arc welding is maintained in the weld zone.

Fluxes of the types defined in Table 10 are modified with metal silicates to produce more economical compositions that contain less manganese and to provide improved weld properties and welding performance. Other flux formulations of higher basicity (higher contents of CaO and CaF_2) have been suggested for greater impact strength and

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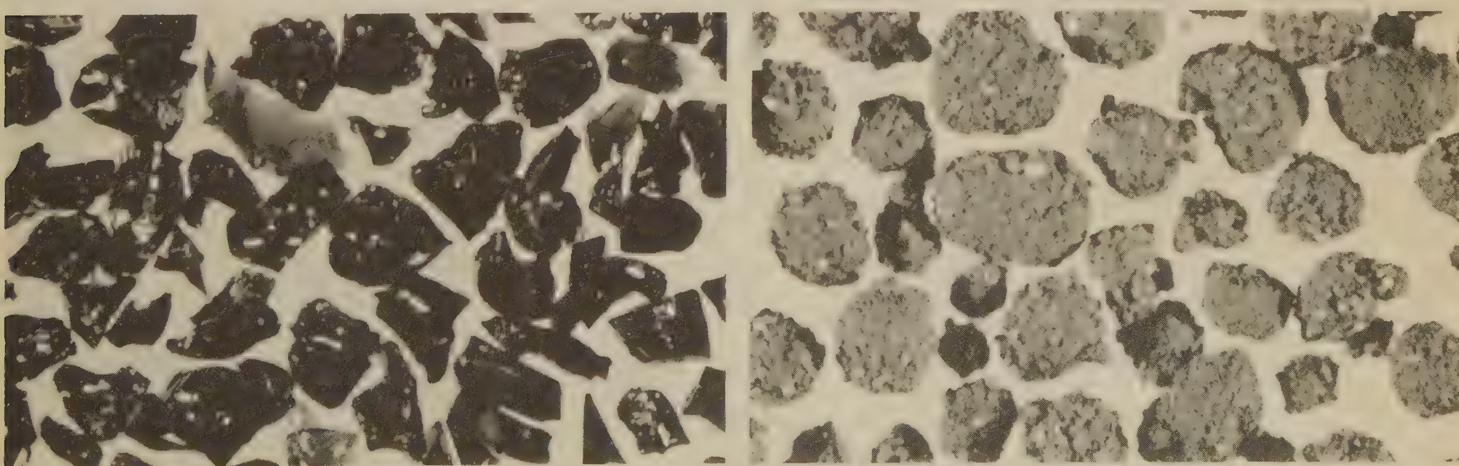


(a) Prefused flux (b) Bonded flux

Fig. 44. The two principal forms of submerged-arc welding flux — prefused and bonded. Both forms shown are of manganese silicate composition and crushed to 12 × 150 (through 0.055-in. opening and retained on screen with 0.0041-in. opening). Magnification, about 8×.

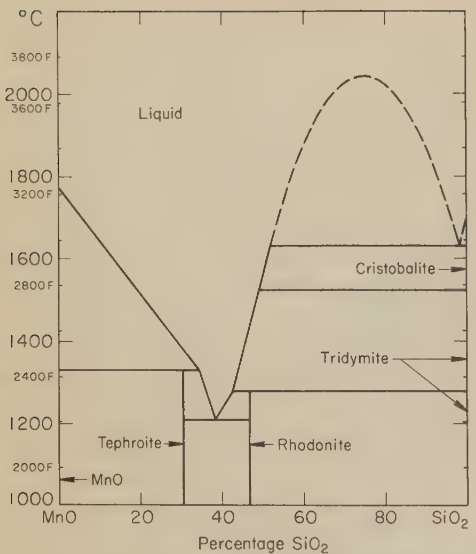


Fig. 45. Phase diagram for the MnO-SiO₂ system (Ref 1)

improved mechanical properties of the weld metal. Arc stability is improved by adding titania. Additions of selected metal oxides provide improved performance in the welding of alloy steels. High-speed performance in welding sheet metal is obtained by adjusting the viscosity – temperature characteristics of the flux. Special fluxes can be formulated to give adequate performance in many applications (Ref 2 and 3).

Comparison With Electrode Coverings. Submerged-arc welding fluxes differ in several important respects from the fluxes used as coverings on electrodes for shielded metal-arc welding. Fluxes for shielded metal-arc welding contain compounds, such as cellulose, that break down in the heat of the arc to provide a shielding gas; compounds with a low work function, such as sodium oxide and potassium oxide, are added to assist in initiating and sustaining the arc; and other substances may be added to facilitate control of penetration, melting rate, and polarity of operation. Submerged-arc welding fluxes do not require most of these additions. The protection afforded by the molten flux and granular burden eliminates the need for generation of shielding gases. The presence of silica and fluoride compounds generally assures satisfactory arc stability, and up to 10% (or more) calcium fluoride can be added to metal silicates to modify arc behavior and increase fluidity of molten flux.

Unlike the coatings used on covered electrodes, whose formulation is complicated by the necessity for the coating to be extrudable and by other production considerations, submerged-arc welding fluxes can be based on simple mineral compounds selected from binary, ternary or quaternary oxide systems. The most common fluxes are based on the $MnO-SiO_2$ system (Fig. 45) or the $CaO-SiO_2$ system, both of which may be combined with alumina, magnesia, zirconia, or titania to form fluxes for particular applications.

Fluxes for covered electrodes and those for submerged-arc welding are classified on a different basis. The most widely used specification for covered electrodes (AWS A5.1-69) classifies electrodes according to the type of material in the flux covering. The AWS specification for electrodes and fluxes for submerged-arc welding (A5.17-69) makes no reference to the chemical nature of the fluxes. Rather, the classification of fluxes is based on mechanical properties of weld deposits made with particular electrodes. In practice, selection of submerged-arc fluxes is based on welding performance, rather than on technical considerations *per se*, and a multiplicity of combinations of electrode and flux are used.

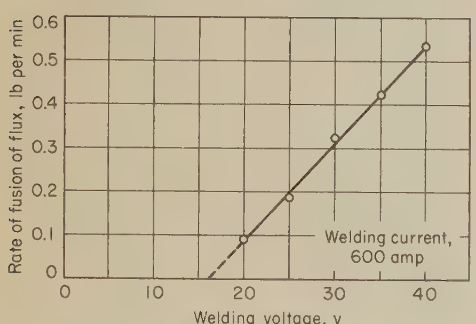


Fig. 46. Effect of increasing voltage on the fusion rate of a calcium silicate submerged-arc welding flux, at a given current

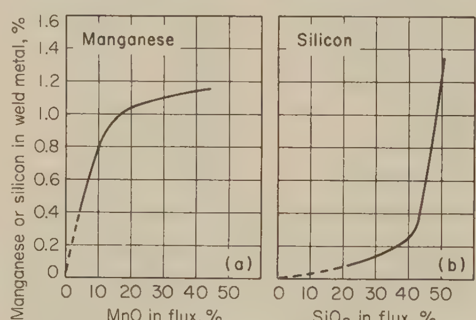


Fig. 47. Effect of MnO and SiO₂ contents of submerged-arc welding fluxes on manganese and silicon contents of weld metal

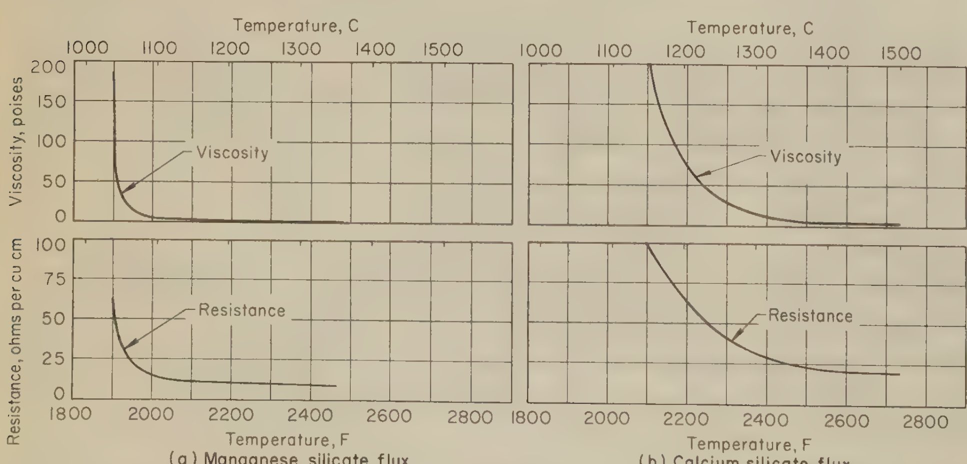


Fig. 48. Effect of temperature on the viscosity and electrical resistance of two types of submerged-arc welding flux

Melting Temperature and Melting Rate of Fluxes

To be effective, a welding flux should have a viscosity at high temperatures that will provide a fluid blanket over the weld metal and protect it from oxidation; it should be brittle at room temperature, to facilitate the removal of slag. Both the melting temperature of the flux and the density of the molten flux must be lower than that of the weld metal so that gases generated between the metal and the flux will permeate the flux. Also, the flux must remain molten until after the weld metal has solidified so that the fluxing action will be complete. Consequently, the upper limit for the melting range of submerged-arc welding fluxes is about 2370 F (1300 C).

The amount of flux fused per minute in submerged-arc welding depends on the welding current and voltage. For a given current, the amount of flux fused per minute increases with voltage, as shown by Fig. 46. In Fig. 46, the zero intercept may be assumed to indicate the anode-plus-cathode potential; this intercept increases with the welding current (see Fig. 52). Under usual practical welding conditions, the weight of flux melted is about the same as the weight of electrode melted.

Effect of Flux Composition on Weld-Metal Composition

During submerged-arc welding, the reactions between liquid weld metal and fused flux are similar to those between molten metal and slag in steelmaking. Removal of impurities from the liquid weld metal and transfer of elements, such as manganese and silicon, between flux and metal follow the technology of molten slag – metal reactions (Ref 4, 5 and 6).

As shown in Fig. 47(a), the manganese content of the weld metal increases rapidly with initial increases of MnO in the flux. Many flux compositions contain about 10% MnO in order to promote the pickup of manganese by the weld metal. A different relationship exists between the SiO_2 content of the flux and the silicon content of the weld metal (Fig. 47b). Normally, a rapid pickup of silicon is not encountered until the SiO_2 content of the flux is approximately 40%. As a result, commercial fluxes are generally restricted to a maximum of about 40% SiO_2, especially fluxes that are to be used for multiple-pass welding.

Some submerged-arc fluxes are formulated to provide control over the transfer of metallic elements. Ferroalloys bonded into the flux can supply alloying elements to the weld metal, to obtain desired properties of the deposit. Oxides added to the flux (Ref 7), such as Cr_2O_3, MoO_3 and NiO, help in the distribution of metallic elements between the molten flux and weld metal. The silicon content of the weld metal is influenced by the Cr_2O_3 content of the flux, the composition of the electrode, the composition of the base metal on which weld metal is being deposited, and the welding technique.

Any factor that affects the time cycle for the flux–metal reaction, or that changes the average temperature of the weld puddle (Ref 6), will affect the distribution of metallic elements between the molten flux and weld metal. Under normal conditions of welding, the speed of travel is probably the most influential factor, although an increase in voltage generally causes additional amounts of metallic elements to transfer to the weld metal.

Viscosity and Conductivity of Fluxes

The viscosity of a welding flux at the weld zone must be high enough to make it impermeable to atmospheric gases and to prevent it from running off the molten weld metal or from flowing in front of the arc, which could lead to molten metal being deposited on top of the flux. On the other hand, during welding, the flux must be fluid enough to permit rapid solution of nonmetallic constituents, such as oxides, and the release of gases from molten metal.

The viscosities of welding fluxes are about 2 to 7 poises at 2550 F (1400 C). The 200-poise viscosity of submerged-arc welding fluxes is typically at about 2000 to 2200 F (1100 to 1200 C).

At room temperature, the granules of submerged-arc welding fluxes are electrical insulators; electrical resistivity decreases with increasing temperature, and the fluxes are highly conductive at the temperatures prevailing in the welding zone.

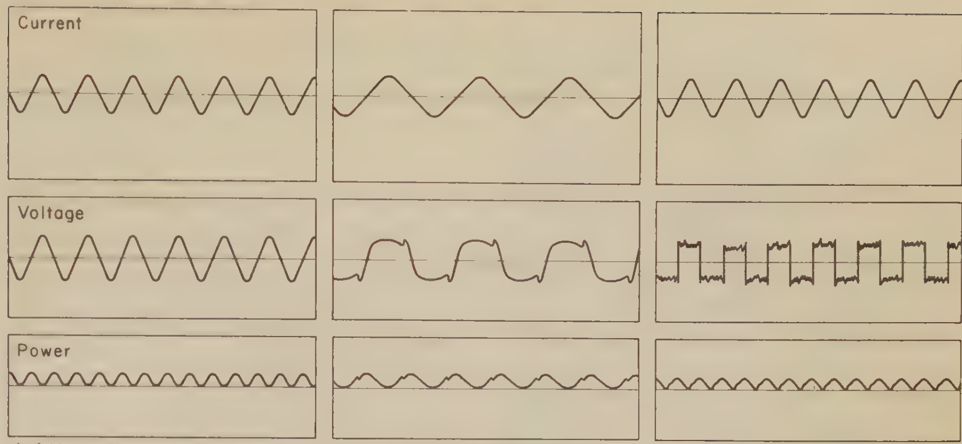
The effect of temperature on the viscosity and electrical resistance of a typical manganese silicate submerged-arc welding flux is shown in Fig. 48(a). This flux has a narrow melting range, typical of a single compound. The effect of temperature on viscosity and electrical resistance of the more complex calcium silicate flux modified with alumina is shown in Fig. 48(b).

Electrical Relations

The type of flux and the welding technique determine the electrical relations in the welding zone. Typical oscillographic traces of current, voltage and power with three different types of flux are shown in Fig. 49. Figure 49(a), for a magnesia-alumina titanate flux, is typical of electroslag welding, in which there is no arc and the welding zone acts as a simple linear resistance in the circuit. Figure 49(c), for a submerged-arc welding flux of the manganese silicate type, is typical also of other welding processes that operate with a normal arc. Figure 49(b), for a calcium silicate flux, is an intermediate combination of resistance and arc heating.

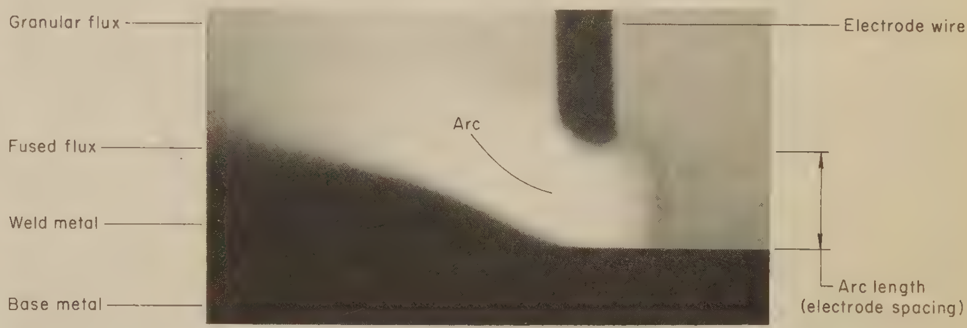
Oscillographic, spectrographic and radiographic studies indicate the presence of a normal arc in the welding zone during submerged-arc welding. In oscillographic studies, the voltage trace (Fig. 49) is the most significant record in determining electrical relationships.

A radiograph from an x-ray study of the submerged-arc welding process is presented in Fig. 50, which shows the positions of the various components in the welding zone. Spatial relations depend on the welding technique, as well as the type of flux. Correlation of arc length with voltage shows that as voltage increases, the length of the welding arc increases. Under the welding conditions given below Fig. 50, arc length was 0.25 in. at 43 volts. At 35 volts, the arc length was 0.08 in.; the arc length increased to 0.14 in. at 38 volts, and to 0.17 in. at 40 volts.



(a) Magnesia-alumina titanate flux. Resistance heating, as in electroslag welding.
(b) Calcium silicate flux. Intermediate combination of resistance and arc heating.
(c) Manganese silicate flux. Arc heating typical of submerged-arc welding.

Fig. 49. Typical oscillographic traces for three types of flux



Welding conditions: Current, 600 amp, dcrp; 43 volts; travel speed, 15 in. per minute; electrode-wire diameter, 5/32 in.; flux, magnesia-alumina silicate type.

Fig. 50. Radiograph of the submerged-arc welding zone. Double size.

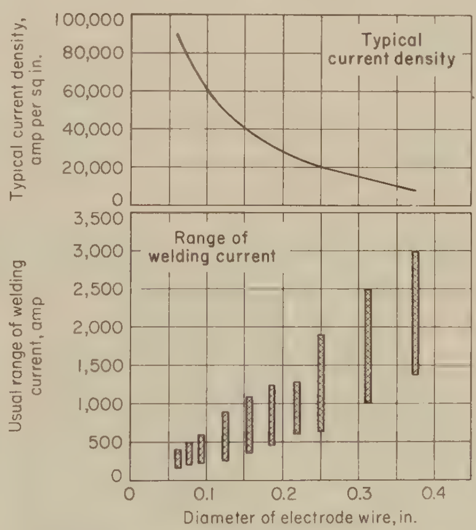


Fig. 51. Typical current densities and usual ranges of current for various diameters of electrode wire in submerged-arc welding

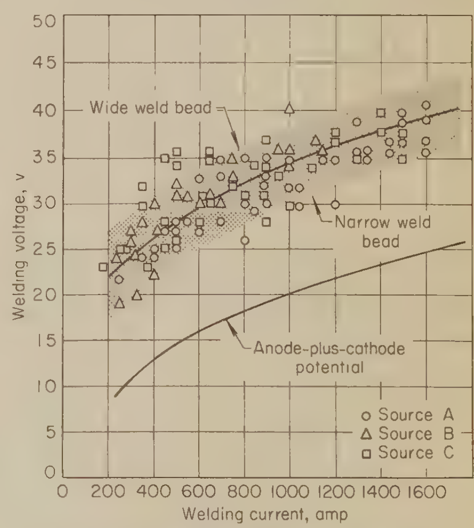


Fig. 52. Current-voltage relations for practical conditions of submerged-arc welding, using a variety of commercial fluxes

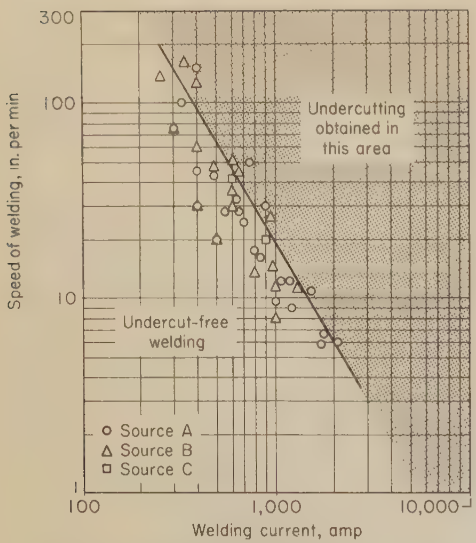


Fig. 53. Current-speed relations for undercut-free welding of steel with a single electrode and various commercial fluxes

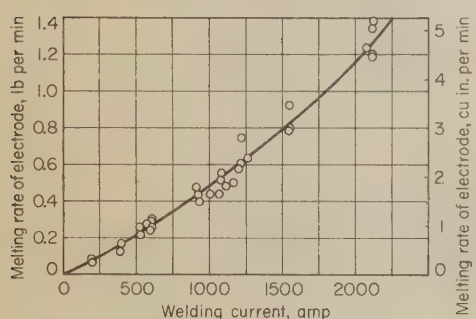


Fig. 54. Current – electrode-melting-rate relations for submerged-arc welding (Ref 9)

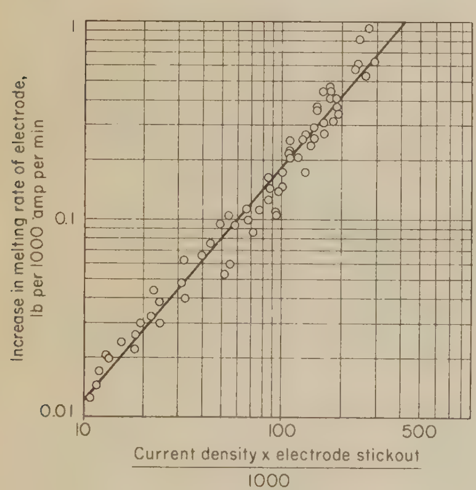


Fig. 55. Increase in electrode melting rate due to I^2R heating (Ref 8)

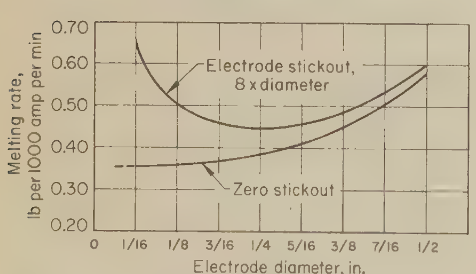


Fig. 56. Effect of electrode diameter and 8-diameter stickout on melting rate (Ref 8)

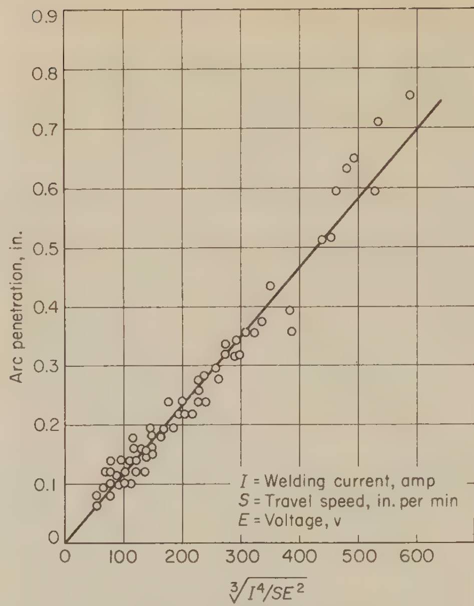


Fig. 57. Effect of welding technique on arc penetration

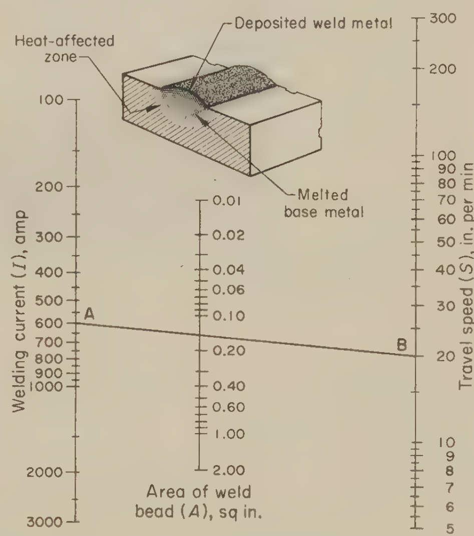


Fig. 58. Alignment chart for determining the area of a weld bead from welding current and travel speed for a given welding technique. Welding voltage, a minor variable, is neglected.

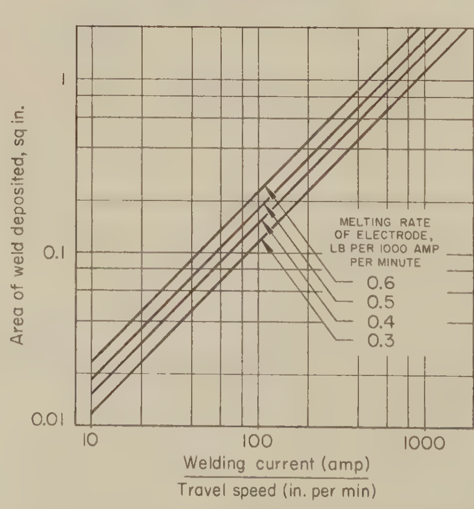


Fig. 59. Effect of ratio of current to speed on the cross-sectional area of weld metal deposited for four rates of electrode melting

Welding Conditions

In submerged-arc welding, the current density in the electrode wire (Fig. 51) is several times greater than in shielded metal-arc welding, and the melting rate of the electrode wire and the speed of welding are increased.

Current-voltage relations typical of industrial applications are shown in Fig. 52. These data suggest that there is a range of about 10 volts for each setting of welding current; the lower voltages give a narrow weld bead, and the higher voltages give a wide bead. Outside the 10-volt working range, soundness of the weld metal deteriorates. Figure 52 shows that as the welding current increases, the working voltage increases. The sum of the anode and cathode potentials increases with increasing current. The amount of submerged-arc welding flux that is fused approaches zero as the voltage decreases toward the anode-plus-cathode potential for each level of current. The decrease in anode-plus-cathode potential is not linear, indicating that there is electrolytic conduction.

The maximum speed of welding, beyond which erratic behavior and undercutting occur, also is controlled by the welding current. In Fig. 53, which is a survey of published data, any combination of current and speed of travel to the right of the diagonal line leads to undercutting.

Techniques have been developed for welding 14-gage (0.078-in.-thick) steel at speeds greater than 100 in. per minute. Single-pass welds in plate 1 in. thick can be made with 1500 amp at 10 in. per minute. Multiple-pass techniques have been developed for joints in heavy plate and joints requiring optimum mechanical properties. Two, three or more electrodes can be fed into a single weld zone in some applications.

Melting Rate

The melting rate of the electrode wire is sometimes expressed in inches or feet per minute, but a more useful unit is pounds per minute or pounds per hour. For comparing applications, the melting rate is sometimes expressed as pounds per minute per ampere, or as pounds per thousand amperes per minute. In submerged-arc welding, the electrode melting rate increases as the current increases, as shown in Fig. 54.

Electrode Stickout. The melting rate of a welding electrode is the sum of the rate due to arc melting and that due to resistance (I^2R) heating in the

Table 11. Data for Use in Calculating I^2R Heating and Electrode Melting Rate

Electrode diameter, in.	Electrode area, sq in.	Pound per foot	Feet per pound	Current density, amp/sq in.(a)
0.030 ...	0.0007	0.0024	416.5	1,414,000
3/64	0.0017	0.0059	170.20	579,600
1/16	0.0031	0.0104	96.15	325,900
5/64	0.0048	0.0163	61.16	208,400
3/32	0.0069	0.0235	42.55	144,900
1/8	0.0123	0.0419	23.86	81,300
5/32	0.0192	0.0654	15.29	52,100
3/16	0.0276	0.0942	10.61	36,200
1/4	0.0491	0.1675	5.97	20,400
5/16	0.0767	0.2617	3.82	13,000
3/8	0.1105	0.3768	2.65	9,050

(a) For current of 1000 amp

length of electrode that extends beyond the contact tube (Ref 8). Electrode stickout is usually taken as the distance from the surface of the base metal to the contact-tube tip, because the distance from the contact-tube tip to the end of the electrode can vary during welding if large globules of weld metal are transferring. Depending on the arc length, the end of the electrode can be above, at, or below the upper surface of the base metal.

The melting rate due to I^2R heating in the electrode stickout is an exponential function of stickout length, current and electrode diameter. The increase in melting rate due to I^2R heating has been shown to depend on current density and electrode stickout (Fig. 55). Both the current density and the electrode stickout depend on the electrode diameter. Typical current densities for various electrode diameters are given in Fig. 51; the melting rate for a practical electrode stickout of eight times the electrode diameter is shown in Fig. 56. Table 11 presents data useful in calculation of electrode melting rate (see also formula in Table 12).

Penetration

The penetration of a weld deposited in a groove or on the surface of the base metal is usually defined as the distance below the original surface to which metal has been melted. Welding current is the most significant variable in determining penetration; travel speed and voltage are less important. Figure 57 shows the combined effect of current, voltage, and travel speed on penetration for a series of experiments with submerged-arc welding. A similar linear relationship has been shown for other arc welding processes, including shielded metal-arc and gas metal-arc welding. The slope of the diagonal line varies with the process, being the greatest for processes that use helium or carbon dioxide shielding gas. For convenience, the empirical equation for arc penetration is also given in Table 12, together with other useful empirical formulas for submerged-arc welding.

Table 12. Empirical Formulas for Submerged-Arc Welding

Electrode Melting Rate, Lb per Min

$$MR = \frac{I}{1000}\left[0.35 + d^2 + 2.08 \times 10^{-7}\left(\frac{IL}{d^2}\right)^{1.22}\right]$$

Area of Weld Bead, Sq In.

$$\text{Log } A = 0.903 \log\left(\frac{I^{1.716}}{S}\right) - 3.95$$

$$A = \frac{I^{1.55}}{10^{3.95}\ S^{0.903}}$$

Weld Dilution, %

$$\%\ \text{dilution} = \left(\frac{A - \dfrac{MR}{0.283S}}{A}\right)100$$

$$= 100 - \frac{353MR}{AS}$$

Arc Penetration, In.

$$P = K\ \sqrt[3]{I^4/SE^2}$$

MR = electrode melting rate, lb per minute
I = welding current, amp
L = electrode stickout, in.
d = electrode diameter, in.
A = area of weld-bead section, sq in.
P = arc penetration, in.
K = process penetration constant (0.0012 for calcium silicate flux)
E = welding voltage
S = speed of travel, in. per minute

In calculations of thermal input and cooling rates, the heat content of the molten weld metal is important. It is proportional to the cross-sectional area of the weld bead, which represents the amount of metal (see inset in Fig. 58) that has been heated to the molten state. For any given welding technique, the efficiency of the process is inherent in the measurement of this area. Weld-bead area increases with increasing welding current and decreases with increasing travel speed. It is affected only slightly by normal changes in arc voltage. The alignment chart of Fig. 58 is based on data for submerged-arc welding, which generally provides for 100% transfer of filler metal.

Dilution

The ratio of base metal melted to weld metal deposited is important in controlling the mechanical properties of the weld metal. Dilution of the weld metal by the base metal can be expressed as the percentage of the bead volume (cross-sectional area times bead length) that is base metal.

Dilution of weld metal by base metal increases with an increasing ratio of current to speed of travel. An increase in voltage may increase the amount of dilution, as a consequence of the slightly lower electrode melting rate that results with the higher-voltage condition.

Dilution for a weld bead can be estimated if the melting rate of the electrode and the process variables are known, by the use of the charts in Fig. 58 and 59 and the formulas in Table 12. Weld-metal cracking usually increases as the amount of dilution by the base metal increases.

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Examples of Submerged-Arc Welding Presented Elsewhere in This Volume

Metal welded	Example	Subject of example
Low-carbon steel	21	Cost of welding trunnions to tank heads by submerged-arc welding vs flux-cored arc welding
	46	Groove design and welding conditions for joining of 1020 and 8620 steel components by submerged-arc vs flux-cored arc welding
	105	Costs and welding conditions for joining of 1010 steel components with two circumferential fillet welds by submerged-arc vs gas metal-arc welding
	121	Times and welding conditions for joining of 1008 or 1010 steel brake drums with two fillet welds at lap joints by submerged-arc vs gas metal-arc welding
	128	Conditions for making filler passes in welding seams in 20-ft-long sections of pipe
	186	Conditions for welding of 1015 steel arms to a 1038 steel shaft
Medium-carbon steel	150	Hard facing of treads on flanged wheels made of 0.30 to 0.40% carbon steel
	154	Hard facing of tractor rollers and idlers made of 1040 steel
	155	Facing of cutting edges on shear blade with stainless steel or cobalt-base alloys
	186	Conditions for welding of 1015 steel arms to a 1038 steel shaft
	194	Hard facing of worn surfaces on a 1030 cast steel shaft
	195	Surfacing a forging made of ASTM A266, class 2, steel to provide a low-carbon steel base to which medium-carbon steel tubes were welded
	224	Conditions for welding a 4130 steel wear ring to a 1025 steel disk
	365	Submerged-arc vs electroslag welding of 20-ft-long seams in ASTM A515, grade 70, steel cylinders
Alloy steel	46	Groove design and welding conditions for joining of 1020 and 8620 steel components by submerged-arc vs flux-cored arc welding
	153	Hard facing of drill collars made of 4145 steel
	207	Repair of discontinuous tears and cracks in alloy steel castings
	220	Welding 3.5% nickel steel pipe sections with stainless steel filler metals
	221	Welding resulfurized 4150 steel with a flux-electrode combination that reduced porosity
	222	Submerged-arc spot welding of carburized and hardened 4027 steel to 1027 steel
	223	Submerged-arc vs shielded metal-arc and gas metal-arc welding of 4130 steel to 4140 steel
	224	Conditions for welding a 4130 steel wear ring to a 1025 steel disk
Stainless steel	268	Groove design and conditions for welding turbine wheels made of type 403 modified
	269	Joint design and conditions for welding type 347 pipe using a backing ring
Malleable iron	241	Conditions for welding a malleable iron casting to a low-carbon steel forging
Heat-resisting alloy	285	Conditions for welding alloy 16-25-6 to 4340 steel with Hastelloy W filler metal
Nickel alloy	355	Conditions for butt welding of 10-ft-diam cylinders made of Invar 36

Gas Metal-Arc Welding (MIG Welding)

*By the ASM Committee on Gas Metal-Arc Welding and Flux-Cored Arc Welding of Steel**

GAS METAL-ARC WELDING (often called MIG welding) is an arc welding process in which the heat for welding is generated by an arc between a consumable electrode and the work metal. The electrode, a bare solid wire that is continuously fed to the weld area, becomes the filler metal as it is consumed. The electrode, weld puddle, arc and adjacent areas of the base metal are protected from atmospheric contamination by a gaseous shield provided by a stream of gas, or mixture of gases, fed through the electrode holder. The gas shield must provide full protection, because even a small amount of entrained air can contaminate the weld deposit.

Gas metal-arc welding overcomes the restriction of using an electrode of limited length, as in shielded metal-arc welding, and overcomes the inability to weld in various positions, which is a limitation of submerged-arc welding. A closely related arc welding process that utilizes tubular electrode wires containing flux is described in the article that begins on page 24.

Advantages. The principal advantage of gas metal-arc welding over shielded metal-arc welding (usually its closest competitor) is greater speed, which is mainly accounted for by: (*a*) continuous feed of filler metal, so that the welder need not stop to replace used-up electrodes, as is required in shielded metal-arc welding; (*b*) absence of slag, which must be removed after each pass when welding with flux-covered electrodes; and (*c*) use of a smaller-diameter electrode wire than for shielded metal-arc welding for a given welding current — thus, current density is higher and weld-metal deposition rate is greater.

Use of the gas metal-arc process results in weld metal with a low hydrogen content, which can be important, especially in welding hardenable steels. The potential for deep penetration with the gas metal-arc process can sometimes allow the use of smaller fillet welds, and produce more consistent root penetration, than with shielded metal-arc welding. Gas metal-arc welding is also better adapted than shielded metal-arc welding for joining of thin sheets, although the gas tungsten-arc process is often used for welding thin sheets when no filler metal is required.

The minimum work-metal thickness usually considered practical for shielded metal-arc welding is about 1/16 in. However, the use of small-diameter wire as filler metal with the gas metal-arc process permits welding of metals considerably thinner than 1/16 in.; the minimum thickness depends greatly on welding position and skill of the welder. With careful control of current characteristics, metal as thin as 0.020 in. can be successfully gas metal-arc welded.

It is often possible to produce welds of higher quality by gas metal-arc than by shielded metal-arc welding, because in the gas metal-arc process there is no slag to contend with. Slag is often the direct cause of weld defects, and it is sometimes an indirect cause, because it can obscure the welder's view of the weld puddle and the arc.

Disadvantages or limitations of gas metal-arc welding as compared with the shielded metal-arc process include:

1. Equipment for gas metal-arc welding is more complex, and consequently is more costly and less portable.
2. In gas metal-arc welding, the electrode holder must be close to the work, and consequently gas metal-arc welding is less adaptable than the shielded metal-arc process for welding in difficult-to-reach areas.
3. In hardenable steels, gas metal-arc welded joints can be more susceptible to weld-metal cracking, because there is no slag cover to reduce the rate of cooling.
4. Gas metal-arc welding requires positive protection from strong drafts, which blow the stream of shielding gas away from the weld; for this reason, the gas metal-arc process may be less practical than the shielded metal-arc process for welding outdoors.

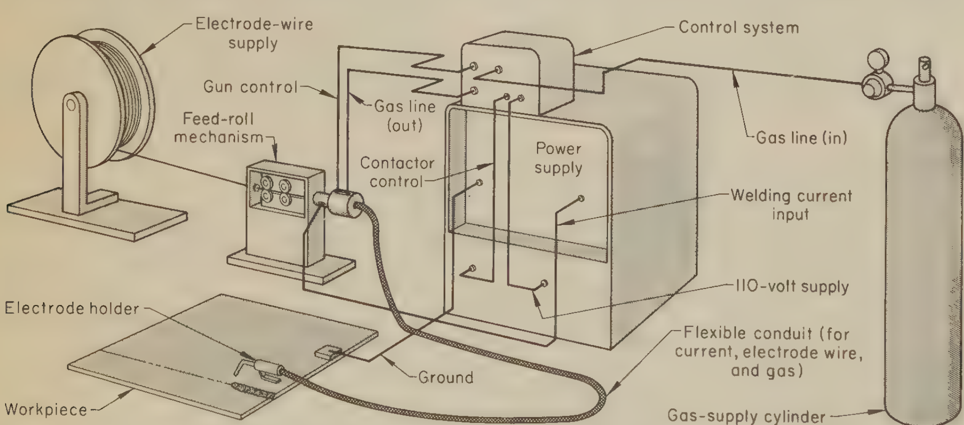

Fig. 1. Schematic of essential requirements for gas metal-arc welding, employing a constant-speed push-type wire-feed system and a constant-voltage power supply

Applicability

In all gas metal-arc welding, the electrode wire is fed automatically to the electrode holder at a controlled rate, even though the electrode holder may be manipulated by the welder. This process cannot be considered manual; it is semiautomatic, machine, or automatic.

In semiautomatic welding, the equipment controls only the electrode-wire feed rate. Manipulation of the electrode is manually controlled. Starting and stopping of the wire feed, of shielding-gas flow, and of current are also manually controlled.

In machine welding, the equipment and setup are fully mechanized but one or more controls require observation and adjustment by a welding operator. The operator starts the operation and performs necessary controlling functions until welding is completed.

In automatic welding, the equipment and setup are fully mechanized and automatically controlled to a degree that requires little or no observation or adjustment by an operator. The operator starts the operation, and the

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Many of the examples presented in this article were contributed by members of other Metals Handbook welding committees. A total of 55 examples of gas metal-arc welding appear in other articles in this volume, as recorded in Table 10 at the end of this article (page 112).

controls take over until welding is completed. Workpieces may or may not be loaded and unloaded automatically.

Metals Welded. The gas metal-arc process was first applied to the welding of magnesium and aluminum alloys and stainless steels, because it was often the only method by which satisfactory welds could be produced at an economical rate.

The nature of the process permits its use for welding of most metals and alloys. However, some metals are more adaptable than others, and there are a few that cannot be welded. Those metals most easily welded by the gas metal-arc process include carbon and low-alloy steels, stainless steels, heat-resisting alloys, aluminum and aluminum alloys of the 3000, 5000 and 6000 series, copper and copper alloys other than the high-zinc alloys, and magnesium alloys.

Metals that can be welded by the gas metal-arc process but that may require special procedures are high-strength steels, aluminum alloys of the 2000 and 7000 series, copper alloys that contain high percentages of zinc (such as manganese bronze), cast iron, austenitic manganese steel, titanium and titanium alloys, and refractory metals. Gas metal-arc welding of these metals may require preheating or postheating of the base metal, use of special filler metals, closer-than-normal control of shielding gas, and use of backing gas.

Metals that have a low melting temperature or a low boiling temperature are not amenable to gas metal-arc welding (or any other arc welding process). Lead, tin and zinc are typical of this group. Zinc, for instance, boils at 1663 F, which is far below the arc temperature, and it produces toxic fumes, as does lead.

High-melting-point metals that are coated with a low-melting-point metal (such as lead, tin, cadmium or zinc) are difficult or impossible to weld satisfactorily, because the welding heat causes fuming of the coating or alloying with the base metal, or both — the result of which is welds with poor mechanical properties. When coated metals are to be welded, the coating should first be thoroughly removed from the joint areas. Postweld repair of the coating over the weld area is essential if the protection afforded by the coating is required at this location.

Although aluminum and its alloys are readily welded by the gas metal-arc process, aluminum-coated steel may cause difficulty in welding, because aluminum vaporizes at a low temperature on aluminum-coated steel.

For further information and examples of practice that deal with gas metal-arc welding of metals other than low-carbon steel, see Table 10 on page 112, and the articles in this volume on welding of specific metals.

Work-Metal Thickness. Gas metal-arc welding can be used successfully for a wide range of work-metal thicknesses (see "Thin Sections", p 93; "Intermediate and Thick Sections", p 94; and "Sections of Unequal Thickness", p 95). Sheet as thin as 0.020 in. can be gas metal-arc welded. Although there is no established maximum thickness, for production welding of steel sections thicker than ½ in., another arc welding process (such as submerged-arc welding or flux-cored arc welding) or electroslag welding often costs less than gas metal-arc welding and leaves a more desirable appearance (see the articles on Flux-Cored Arc Welding, page 24, Submerged-Arc Welding, page 46, and Electroslag Welding, page 373).

The limitation on work-metal thickness is sometimes determined by fillet size; a ¼-in. fillet weld is the maximum practical size for most applications.

Welding Position. Gas metal-arc welding is generally considered to be the most versatile of all arc welding processes in terms of the welding positions in which it can be used. As in other welding processes, welding is most efficient in the flat and horizontal positions, but gas metal-arc welding is at least equal to shielded metal-arc welding in the other positions.

Principles of Operation

Operating principles of gas metal-arc welding differ considerably from those of the shielded metal-arc process. The covering on the electrodes used in shielded metal-arc welding contains deoxidizers, and sometimes alloying elements, that contribute favorably to the soundness and mechanical properties of the weld metal. In addition to providing a slag blanket that protects the weld puddle, the covering oxidizes and decomposes to produce a shielding gas that displaces the oxygen-rich atmosphere from the region of the arc stream (see Fig. 1 in the article on Shielded Metal-Arc Welding). The covering also controls arc characteristics, primarily by producing an ionizing gas that ensures arc stabilization, and it can affect metal transfer in the various welding positions (flat, horizontal, vertical, or overhead).

In gas metal-arc welding, the objectives are similar, but they are achieved by a different approach. First, the desired arc characteristics are achieved by control of voltage-amperage relationships, shielding gas, and reactance in the power circuits. Second, metallic elements that have higher affinity for oxygen than has iron are added to the electrode wire to serve as deoxidizers and to provide the weld deposit with the desired physical and mechanical properties and weld soundness. Finally, the oxygen of the atmosphere is displaced by flooding the arc-stream area with a shielding gas from a nozzle that is close to, or coaxial with, the electrode wire where it emerges from the electrode holder.

Essential requirements for gas metal-arc welding are: (*a*) a power supply that provides sufficient voltage to push the current across the gap to make the arc, and sufficient current to melt the electrode to make the weld deposit; (*b*) a wire feeder that continuously advances the electrode as it melts; (*c*) a smooth flow of shielding gas; and (*d*) an electrode holder that carries the current, electrode wire, and shielding gas.

These major essentials are illustrated schematically in Fig. 1. Here the wire-feed system is of the constant-speed, push type, by means of which a specific rate of wire feed can be obtained. The power supply is a constant-voltage type, which will maintain any desired voltage output within its capability, regardless of current flow. Under these conditions, only enough current will flow to melt the electrode wire at a rate equal to that of the wire feed.

Arc Characteristics

The types of arc obtainable in gas metal-arc welding are identified by their mode of metal transfer. These modes of transfer are commonly referred to as spray, globular, short circuiting, and pulsed, although the pulsed arc is a form of spray arc.

Spray-Arc Mode. In a spray arc, the metal is transferred from the end of the electrode wire to the puddle in an axial stream of fine droplets. This condition is illustrated in Fig. 2(a). These small droplets emanate from the tapered end of the electrode; one droplet follows

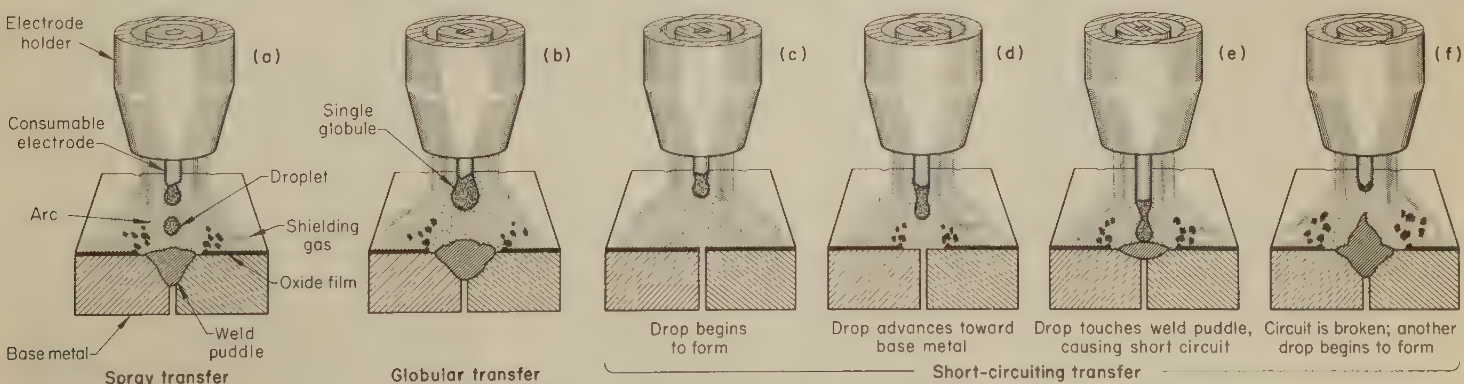


Fig. 2. Modes of metal transfer in gas metal-arc welding: (a) *spray transfer;* (b) *globular transfer;* (c) to (f) *steps in short-circuiting transfer*

another, but they are not connected. The sizes of the droplets may vary, but in a spray arc the maximum diameter is less than that of the electrode wire.

The spray arc occurs at high current density, and generally with argon or an argon-rich shielding gas. A true spray arc cannot be obtained with a shielding gas composed entirely of carbon dioxide.

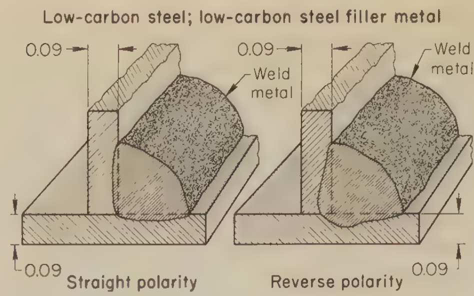
The spray-arc mode of transfer gives high heat input, maximum penetration, and a high deposition rate. In welding steel, it is generally limited to welding in the flat position and the horizontal fillet position.

Globular transfer occurs at lower current densities and is characterized by the formation of a relatively large drop of molten metal at the end of the tapered electrode wire (Fig. 2b). The drop forms at the end of the electrode wire until the force of gravity overcomes the surface tension of the molten drop, at which time the drop falls into the weld puddle. Globular transfer occurs with all types of shielding gases, but it cannot be used for out-of-position welding. If overhead welding were attempted using globular transfer, the molten electrode metal would fall downward into the electrode holder nozzle.

The short-circuiting mode of transfer is used in many applications of gas metal-arc welding. It is especially well adapted to welding of thin sections, because heat input is low; it is less often used for welding thick sections. This mode of transfer permits welding in any position and occurs with carbon dioxide, argon – carbon dioxide mixtures, and helium-base shielding gases.

Steps that occur with the short-circuiting mode of transfer are shown in Fig. 2. At the start of the short-circuiting-arc cycle, the end of the electrode wire melts into a small globule of liquid metal (Fig. 2c). Next, the molten metal moves toward the workpiece, taking the form shown in Fig. 2(d). Then, the molten metal makes contact with the workpiece, creating a short circuit. At this stage of the cycle, metal transfer is by gravity and surface tension and the arc is extinguished (Fig. 2e). Finally, the molten metal bridge is broken by pinch force, the squeezing action common to current carriers, the amount and suddenness of pinch being controlled by the power supply. At this stage, the electrical contact is broken and the arc is re-ignited (Fig. 2f). With the arc renewed, the cycle begins again. Frequency of arc extinction and re-ignition varies from 20 to 200 times per second, in accordance with preset electrical conditions.

Figure 2(c) to (f) shows the low-current short-circuiting arc. As the current density is increased, using carbon dioxide shielding gas, the molten metal transfer moves from a high-frequency rate of short circuits to a lower rate of short circuits, detaching much larger molten metal drops. At the higher current densities and normal arc voltages, metal transfer is much more violent. Short-circuiting transfer is usually associated with lower current density and a rather exact arc-voltage setting. If, for example, a 0.035-in.-diam steel electrode wire is fed at a rate requiring



Joint type	T
Weld type	Fillet
Welding position	Horizontal
Electrode wire	1/32-in.-diam low-carbon steel
Shielding gas	Carbon dioxide
Current	120 amp, dc
Voltage	19 v
Melting rate	280 ipm

Fig. 3. Depths of penetration obtained in gas metal-arc welding with straight-polarity and reverse-polarity direct current under otherwise identical conditions

120 amp of current, and carbon dioxide shielding gas is used, an excellent short-circuiting mode of transfer requires arc voltage of about 19 to 20 volts. If the arc voltage is increased to 25 to 26 volts, the short-circuiting mode of transfer reverts to a mild type of globular transfer. Depth of penetration decreases as current density decreases, except for a minor effect on penetration from arc voltage. A decrease in arc voltage can result in a slight increase in penetration, because the decreased arc voltage with carbon dioxide shielding is accompanied by a shorter arc length.

Pulsed-arc transfer is a spray-type transfer that occurs in pulses at regularly spaced intervals rather than at random intervals. In the time interval between pulses, the welding current is reduced and no metal transfer occurs.

The pulsing action is obtained by combining the outputs of two power supplies working at two current levels. One acts as a background current to preheat and precondition the advancing continuously fed electrode; the other power supply furnishes a peak current for forcing the drop from the electrode to the joint being welded. The peaking current is a half-wave direct current; because it is tied into line frequency, drops will be transferred from the electrode to the joint 60 or 120 times per second.

Electrode-wire diameters of 0.045 to 1/16 in. are most commonly used. The pulsed-arc mode is capable of welding thinner sections than are practical with conventional spray transfer, because heat input is less. Also, because of the low heat input, distortion is less. The pulsed-arc mode of transfer is suited to all welding positions.

Power Supplies

Alternating current is seldom used in gas metal-arc welding. Direct current with reverse polarity is used for most applications, although straight-polarity direct current is sometimes used when penetration must be minimum. Figure 3 compares the depths of penetration obtained in welding with straight and reverse polarity under otherwise identical conditions.

Many types of direct-current power supplies are available, including the rotating types (generators driven by electric motors or internal-combustion engines) and the static types (selenium or silicon rectifiers). Either of these types is available with constant current (drooping voltage) or constant voltage (constant potential).

Constant-current power supplies can be used for shielded metal-arc welding as well as for gas metal-arc welding. A typical volt-ampere curve for a constant-current power supply is illustrated in Fig. 4(a). The high open-circuit voltage (up to 80 volts, and usually about twice the rated voltage) is provided mainly to ensure reliable arc initiation when covered electrodes are used, but it is not required for gas metal-arc welding.

In gas metal-arc welding, when the electrode wire touches the grounded workpiece, the arc length, and therefore the arc voltage, is zero. Thus, short-circuit current flows, melting the wire and initiating the arc instantaneously. As the resistance of the arc increases and the short-circuit current decreases, the voltage rises to the operating range, to a value dictated by the machine setting and its volt-ampere curve. Two characteristics of a constant-current power supply are:

1. Limited short-circuit current capacity — usually 1½ to 2½ times the rated current
2. Ability to maintain a relatively constant current output throughout the normal variations in arc length resulting from manual manipulation of the electrode holder.

The first characteristic serves to protect the machine and the operator.

The use of constant-current power supplies for gas metal-arc welding is rapidly decreasing. They are still used in some plants where both gas metal-arc and shielded metal-arc welding are done, because of their suitability, with limitations, for both processes.

Constant-voltage power supplies, of either the motor-generator type or the transformer-rectifier type, are generally preferred and widely used for gas metal-arc welding. With this type of power supply, the voltage remains nearly constant regardless of the current drawn.

Figure 4(b) shows a typical volt-ampere curve that characterizes the constant-voltage type of power supply. Open-circuit voltage is usually in the range of 40 to 50 volts, with rated voltage at about 35 volts. Because of the relatively small amount of slope in the volt-ampere curve, surging variations in the current will occur when welding is done at low current density. For this reason, a current-stabilizing system may be required for gas metal-arc welding.

Most constant-voltage power supplies are equipped with some means of changing the slope of the volt-ampere curve. This slope control has the effect of limiting the amount of short-circuit current that a power supply can deliver.

A set of theoretical curves that illustrate slope control is shown in Fig. 4(c). In this instance, the voltage is established at 25 volts. Without slope control, there is essentially no slope (uppermost

curve in Fig. 4c). Slope may be added until an extremely steep slope is obtained (lowest curve in Fig. 4c).

Power supplies are available with fixed, stepped, or stepless slope controls. Slope controls are also known as arc stabilizers. They are not always necessary for high current density or for spray-type arcs. For best results, however, they are required when welding is done with small-diameter (0.020 to 0.045 in.) electrode wire at relatively low current and voltage.

For rectifiers, the most efficient way of achieving slope control is by use of a variable reactor in the primary supply circuit (alternating-current side). Another, but less efficient, method is the use of a resistor on the direct-current side. Slope control on a motor-generator power supply is accomplished by the type and position of field and armature windings and the method by which these windings are connected. For instance, on a shunt-wound motor, slope control is obtained by varying the excitation of the shunt. Motor-generators are not designed for ease of slope control, as are rectifier-type power supplies.

Variable inductance may also be an added feature of constant-voltage power supplies. The addition of variable inductance in the output circuit has proved beneficial in developing a stable dc low-current short-circuiting welding arc using 0.030 to 0.045-in.-diam electrode wire and carbon dioxide shielding. Slope control limits the maximum short-circuit magnitude, and inductance control regulates the rate of rise or decrease of welding current. When inductance is insufficient, as the molten end of the electrode wire dips into the weld puddle and short circuiting occurs, the welding current rises rapidly, which causes expulsion of the wire free of the puddle, resulting in weld spatter. Too much inductance results in an insufficient rate of current rise and will cause the electrode wire to stub, almost as if the voltage were set too low.

Control of inductance is obtained by use of a variable reactor in the secondary circuit (direct-current side) of the power supply.

Selection of Power Supply

Power supplies for gas metal-arc welding differ in at least four major respects, each of which must be considered when choosing a power supply for a given application:

1 General type; that is, motor or engine driven, or transformer-rectifier
2 Size (current capacity)
3 Current characteristics (constant current or constant voltage)
4 Degree of complexity, and thus of versatility for a variety of conditions.

The choice between a motor-generator and a transformer-rectifier will be influenced by the supply of current already available in the locations where welding is to be done. If this is ample, transformer-rectifiers are usually the better choice, because they are less expensive and easier to maintain than motor-generators. They are the most popular choice for production welding.

Size, in terms of output current, will be governed by the maximum current that will be needed, or can be foreseen, for a specific installation. This is usually the most important requirement.

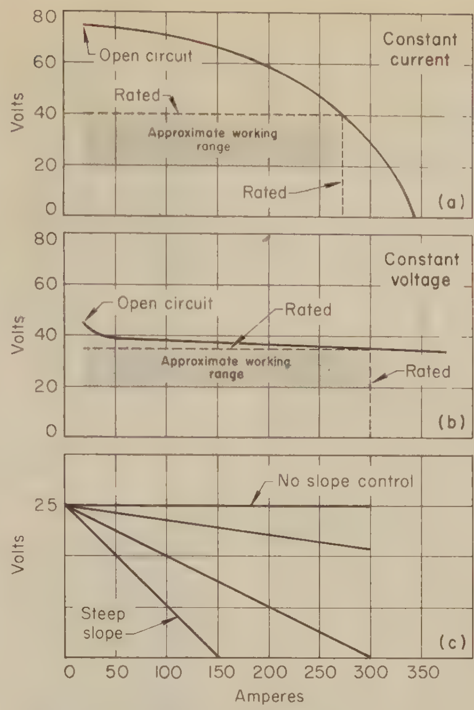


Fig. 4. (a) and (b) *Typical volt-ampere curves for constant-current and constant-voltage power supplies.* (c) *Effect of varying slope control on volt-ampere curves.*

Although many welding machines with constant-current power supplies are still in use, new machines purchased for use in gas metal-arc welding (or flux-cored arc welding) are usually of the constant-voltage type, because their current characteristics are better suited to the process.

The degree of complexity, principally in terms of the ranges and types of adjustment of the power output, is an important factor in selection. Rectifier-type constant-voltage power supplies of the same capacity can vary in cost by a factor of two or three, depending on how they are equipped. The simplest type has a fixed volt-ampere slope and a fixed amount of inductance in the circuit. If such a machine is designed for a particular application (base-metal thickness, fit-up, fillet size, or other specific operating condition), it will do as good a job as a more complex machine, but if welding conditions are changed, results with this machine might be unacceptable.

The most complex machines are those equipped with stepless slope control, stepless control of inductance, and voltage control over a wide range. Such machines can be used with almost any set of conditions that may be encountered in gas metal-arc welding. For example, with a machine of this type, an experienced welder can weld two ¼-in.-thick plates, using high current density and a spray-type arc; a nearly flat volt-ampere slope and a large amount of inductance would be used. In a few minutes, the slope, inductance, voltage, and current (current is determined by the rate of wire feed) could be changed to enable the machine to be used with a short-circuiting arc for welding thin sheet.

If a power supply is to be used mainly for high production, under a fixed set of welding conditions, a simple, comparatively inexpensive machine is the best choice. If a power supply is to be used under various welding conditions, a more versatile (and more costly) machine will be required.

Electrode Holders

Electrode holders for gas metal-arc welding are frequently called guns, because some of them resemble a pistol in outward appearance, or torches, as their counterparts used for gas tungsten-arc welding are often called.

Electrode holders for use with the gas metal-arc process are considerably more complex than are those used for shielded metal-arc welding. First, it is required that the electrode wire should move through the holder at a pre-established rate; second, the holder must be designed to transmit current to the electrode wire and to carry the shielding gas. The method of cooling the holder (air or water), and the location of controls for feeding the wire and the shielding gas, can add to the complexity of electrode holders.

Electrode holders for manual manipulation (semiautomatic welding) may be either air cooled or water cooled. The essentials of a typical air-cooled holder are shown in Fig. 5(a). Important components of this conventional gun-type holder are: (*a*) the nozzle (ordinarily made of copper or beryllium copper), which usually has an inside diameter of ⅜ to ⅞ in., depending on the size of the holder; (*b*) the copper alloy contact tube (also called the contact tip), which guides the electrode wire through the nozzle and also supplies the current to the electrode wire; (*c*) the wire-feed conduit, through which the electrode wire is fed from the source; and (*d*) the duct that supplies the shielding gas to the nozzle. Most hand-manipulated electrode holders have a trigger or lever switch for starting or stopping wire feed and gas flow simultaneously.

For some applications, the contact tube is purposely bent (see detail at lower right in Fig. 5), to ensure positive contact with the moving electrode wire. The curved-neck type of holder (Fig. 5a) ensures positive contact without the need for a bent contact tube. A curved-neck electrode holder is usually preferred for welding in all positions.

The water-cooled type of manual electrode holder is similar to the air-cooled type, with the addition of ducts that permit the cooling water to circulate around the contact tube and the nozzle. Cooling with water decreases adherence of weld spatter to the nozzle. Figure 5(b) shows the essential components of a typical water-cooled manual holder.

The choice between air-cooled and water-cooled holders is based on the type of shielding gas, welding current, voltage, joint design, and existing shop practice. For equivalent welding currents, water-cooled holders operate at considerably lower temperatures.

Arcs shielded with carbon dioxide transfer the least amount of heat to the electrode holder. Arcs shielded with

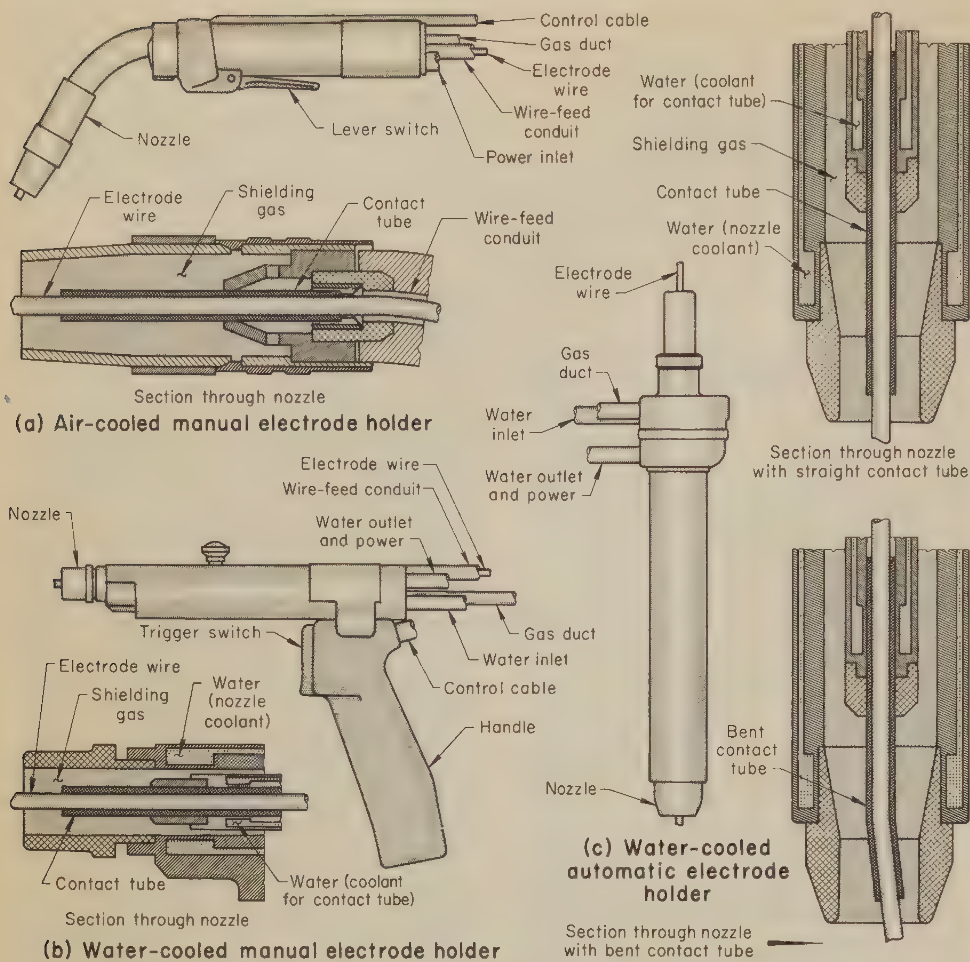


Fig. 5. Details of three types of electrode holders. See text for discussion.

argon, argon-oxygen, helium, helium-oxygen, or argon and carbon dioxide transfer more heat to the electrode holder. However, the type of joint has more influence on the amount of heat transferred to the electrode holder than does the shielding gas. In welding a corner joint or a T-joint, far more heat will be transferred to the electrode holder than in welding a butt, lap or edge joint, in which the heat dissipates in various directions.

Because the ability to absorb heat depends on the mass of the electrode holder, air-cooled holders are heavier for a given rating than are water-cooled holders. Power cables that are cooled only by radiation are also more massive than are water-cooled cables.

The shielding gas used influences the maximum current for air-cooled electrode holders. Because carbon dioxide causes the electrode holder to operate at a lower temperature than argon, higher current can be used with carbon dioxide shielding. Air-cooled electrode holders are rated at 500 amp or less.

Water-cooled holders and power cables are used in applications requiring current ranging from 200 to 750 amp. However, when such electrode holders are manually manipulated, use of the high end of this range depends greatly on whether the welder can tolerate the heat radiated from the arc and from the weld deposit.

Designs of electrode holders vary considerably, depending on the particular manufacturer and specific requirements. For instance, in the three types of holders illustrated in Fig. 5, the electrode wire usually is supplied from a separate and remote push-type wire-feed mechanism through the flexible conduit. One modification of these holders incorporates a small motor in the handle and feeds the electrode wire by pulling it from a remote source. Another modification has a self-contained wire-feed mechanism, as well as its own self-contained wire supply on a spool. Capacity of the spool is usually 1 to 2½ lb of wire.

Many electrode holders are designed with a curve just behind the nozzle so that their outward appearance resembles a gas torch (see Fig. 5a). Many welders find electrode holders of this design easier to manipulate than the straight-neck types.

Electrode holders for automatic or machine welding (in which the electrode holder is held and guided by mechanical means) are also available in a variety of sizes and designs, and can be cooled by either air or water. Major components of a holder for automatic welding are generally the same as those of holders that are manually manipulated. A typical electrode holder for use in machine or automatic welding is shown in Fig. 5(c), together with sections showing straight and bent contact tubes. In some models of both the air-cooled and water-cooled types, the shielding gas is conveyed to the arc area through external passages, instead of through internal passages as in the electrode holders shown in Fig. 5.

Wire-Feed Systems

Numerous types of wire-feed systems are available, of which most are sufficiently flexible to handle a range of wire compositions and sizes. However, it is desirable to choose a system that is best for the particular application.

Most wire-feed systems are of the constant-feed type; that is, the rate of feed (in inches per minute) is established before welding begins. The feed is started and stopped by a switch on the electrode holder for semiautomatic welding, or by other start and stop controls on automatic equipment.

Variable-speed wire-feed systems are adaptable only to constant-current power supplies, and therefore are used less than the constant-feed types.

Wire-feed systems may be of the push type, the pull type, or the push-pull type. The type used depends mainly on the size and composition of electrode wire used, and sometimes on the distance between the wire reel or spool and the electrode holder.

Push-Type Wire-Feed Systems. Most wire-feed systems are of the push type (Fig. 1), in which the wire is pulled from a coil, a spool or a barrel by means of feed rolls and is pushed through a flexible conduit (wire-feed cable) to which the electrode holder is attached. Length of the conduit can be up to 10 ft for steel electrode wire and up to 6 ft for aluminum electrode wire, depending on the column strength of the wire.

If spools or coils are used, some type of friction braking device is usually incorporated in the spindle of the spool to prevent overrun of the wire when the feed motor is stopped. Push-type wire-feed systems are available that can handle hard solid wire from 0.030 to 0.125 in. in diameter, and soft solid wire from 0.045 to 0.093 in. in diameter. The terms "hard" and "soft" refer generally to ferrous and nonferrous wires, respectively.

The system illustrated in Fig. 1 is typical, although there are many variations among systems from different manufacturers. For instance, the feed-roll mechanism in this system has four driven rolls. Many utilize only two rolls, one of which (usually the lower) is driven. Ordinarily, the lower roll (or each of the lower two rolls) has a circumferential V-groove. The upper rolls do not have grooves, but sometimes are knurled to ensure a positive grip on the wire. Regardless of type, a feed-roll mechanism must be designed so that roll pressure on the wire can be increased or decreased as required.

Pull-Type Wire-Feed Systems. Electrode holders that incorporate a wire-feed driving mechanism are also available. The most popular type has a small drive motor in the handle and an attached 4-in.-OD spool of wire. The unit is compact and can easily be manipulated manually. The equipment is relatively delicate, and is best suited to use with electrode wire having a diameter less than 0.045 in. It is particularly useful when welding thin sections, when

the total weight of weld deposit is low, and when the work must be done in a confined space.

Another pull-type wire-feed system is constructed with a gearbox and drive rolls in the electrode holder. Wire is pulled through a conduit from a spool or a coil. The gearbox and drive rolls can be powered either by a motor in the handle of the electrode holder, or by a flexible shaft from a motor located in a console near the source of wire. This system has the advantage that it can be used with small-diameter wires and at the same time retain the advantage of using maximum-size spools or coils. The electrode holder is less portable than when the self-contained pull-type system is used. Portability is about equal to that of a holder equipped with a push-type system.

Push-pull wire-feed systems are particularly suited to use with low-strength wires. The electrode holder is fitted with a motor and drive rolls and is used as the master unit for controlling the speed of wire feed. It receives wire through a flexible conduit, the other end of which is attached to a remote wire-drive mechanism. The speed of the remote mechanism is adjusted to keep the wire in tension. Small-diameter wires (even soft aluminum alloy wires) can be moved 50 ft or more from the source to the electrode holder by a push-pull system. The conduit may have a plastic liner to reduce drag.

Variable-speed wire-feed systems are used only with constant-current power supplies, because they depend on deviations in arc voltage to increase or decrease the rate of wire feed. These systems usually employ variable-speed series-wound direct-current motors. A series-wound motor with a variable resistor is connected in parallel with the welding arc. A current relay is placed in the welding circuit to prevent the drive motor from operating when the welding current is not flowing. To start the arc, it is necessary only to ground the electrode wire. When the arc starts, short-circuit current closes the control relay, and the drive motor also starts. Variable-speed wire-feed systems are self-regulating, because once the wire-feed rate is set, any deviation in arc voltage results in a corresponding change in motor speed. For instance, if there is a reduction in voltage due to surface irregularity, the drive motor will slow down, allowing the arc length to re-establish itself. Welding is stopped by breaking the arc, and thus allowing the current relay to drop out and stop the wire feed.

Maintenance. Wire-feed systems incorporate numerous components that are comparatively delicate, so that a regular program of preventive maintenance is mandatory for prevention of feeding difficulties.

It is especially important that the electrode-wire conduit be kept clean. Common practice is to clean the conduit after each spool of wire is used. If spools are large, more frequent cleaning may be necessary.

Cleaning of the conduit is achieved by removing the wire and blowing clean air through the conduit in the reverse direction from usual flow. In many shops, because clean air is not available, the conduit is cleaned by blowing it out with shielding gas. Oxygen should never be used for this purpose.

Table 1. AWS Classifications and Composition Limits for Electrode Wires for Gas Metal-Arc Welding (AWS A5.18-69)

AWS classification	Composition, %: C	Mn	Si	P, max	S, max	Other
Mild Steel Electrodes(a)						
E70S-1 ..	0.07-0.19	0.90-1.40	0.30-0.50	0.025	0.035	.....
E70S-2 ..	0.06 max	0.90-1.40	0.40-0.70	0.025	0.035	0.05-0.15 Ti, 0.02-0.12 Zr, 0.05-0.15 Al
E70S-3 ..	0.06-0.15	0.90-1.40	0.45-0.70	0.025	0.035	.....
E70S-4 ..	0.07-0.15	0.90-1.40	0.65-0.85	0.025	0.035	.....
E70S-5 ..	0.07-0.19	0.90-1.40	0.30-0.60	0.025	0.035	0.50-0.90 Al
E70S-6 ..	0.07-0.15	1.40-1.85	0.80-1.15	0.025	0.035	.....
E70S-G ..	No chemical requirements					
Low-Alloy Steel Electrodes						
E70S-1B .	0.07-0.12	1.60-2.10	0.50-0.80	0.025	0.035	0.15 max Ni, 0.40-0.60 Mo
E70S-GB .	No chemical requirements					
Emissive Electrode(a)						
E70U-1 ..	0.07-0.15	0.80-1.40	0.15-0.35	0.025	0.035	.....

(a) Nickel, chromium, molybdenum and vanadium may be present, but are not intentionally added.

Table 2. Minimum Mechanical Properties, and Suitable Shielding Gases and Direct-Current Polarity, for the Classes of Electrodes Listed in Table 1 (A5.18-69) (a)

Tensile strength, min:	
All classes	72,000 psi(b)
0.2% yield strength, min:	
All classes	60,000 psi(b)
Elongation in 2 in., min:	
All classes except E70S-1B	22%(b)
E70S-1B	17%(b)
Suitable shielding gas:	
E70S-1	Argon plus oxygen(c)
E70S-2 and 3	Argon plus oxygen(c); carbon dioxide
E70S-4, 5 and 6; E70S-1B	Carbon dioxide
E70U-1	Argon plus oxygen(c); argon
E70S-G and E70S-GB	Not specified
Polarity of direct current:	
E70S-1 through 6; E70S-1B	Reverse
E70U-1	Straight
E70S-G and E70S-GB	(d)

(a) As-welded mechanical properties as determined from an all-weld-metal tension-test specimen, prepared with the shielding gas and current polarity shown. (b) Except for E70U-1 electrode, for each increase of one percentage point in elongation over the minimum, the tensile strength or the yield strength, or both, may decrease 1000 psi to a minimum of 70,000 psi for the tensile strength and 58,000 psi for the yield strength. (c) 1 to 5% oxygen. (d) Type and polarity of current are not specified.

Electrode Wire

Electrode wire for gas metal-arc welding is a high-purity wire of closely controlled chemical composition. The use of ordinary wire generally results in defective welds. Not only must wire composition be closely controlled, but surface condition of the wire must be good, and variations in diameter must be minimal. Surface condition and diametral accuracy both have a marked influence on feeding characteristics. To protect surfaces during storage, most steel electrode wire is flash copper plated. The copper plate also helps to provide good feeding characteristics, and has no adverse effect on the composition of the weld deposit.

Most specifications permit a variation in diameter of ±0.001 in. for wires up to 0.040 in. in diameter, ±0.0015 in. for wires from 0.040 to 1/16 in. in diameter, and ±0.002 in. for wires larger than 1/16 in. in diameter.

It is also important that electrode wires be of uniform hardness (usually measured by tensile strength). Wires that vary in mechanical properties from one package or coil to another are likely to result in erratic feeding behavior.

Proper storage and handling of wire is important for maintenance of wire condition. Oxidized wire impairs welding characteristics, and damage in handling that causes bends or kinks can make feeding difficult.

Composition of electrode wire has a significant effect on results. Because of the importance of electrode composition many large users of electrode wire have established their own specifications, which they have developed from their own experience.

Table 1 lists AWS classifications and composition limits for ten different types of electrodes that are used for gas metal-arc welding of low-carbon steels. For compositions of electrode wire used for welding other metals, see the articles in this volume that deal with the welding of specific metals.

Ranges of carbon content for some of the electrode wires shown in Table 1 are quite wide — sometimes too wide to ensure consistent performance — which explains in part why many users of welding electrodes have established their own specifications on composition. Some have found that ±0.03% carbon is the maximum variation that can be tolerated in critical applications. Most users prefer electrode wires of low carbon content (0.06 or 0.07%), because the carbon content of the base metal is generally higher than this and the base-metal dilution that occurs during welding increases the carbon content of the deposit.

Mechanical Properties. Table 2 shows the minimum mechanical properties specified by AWS for the classes of electrode listed in Table 1, and indicates the shielding gases and the polarity of direct current suitable for use with the various electrodes.

Selection of composition is influenced by the shielding gas used, type of arc (spray, globular or short-circuiting), welding position, service requirements, and condition of the steel being welded. Cost of electrode wires should be considered only after the above requirements have been satisfied. The first six compositions listed in Table 1 do not vary significantly in cost when purchased in the same size, quantity, and type of package. Low-alloy steel electrode E70S-1B may cost as much as

Table 3. Typical Packaging of Steel Electrode Wire for Gas Metal-Arc Welding

Package size, in.	Package weight, lb	Wire diameters, in., available in package sizes in column 1: 0.020	0.025	0.030	0.035	0.045	1/16	5/64	3/32	1/8
Spools										
⅝ ID, 4 OD, 1½ wide	2½	...	...	...	X	X	...	...	...	...
2 ID, 11¾ OD, 4 wide	15	X	X	...	...	...	...	...	...	...
2 ID, 11¾ OD, 4 wide	25	...	...	X	X	X	X	X	X	X
2 ID, 14 OD, 4 wide	60	...	...	X	X	X	X	X	X	X
Coils										
2½ ID, 6 OD, 1½ wide	9	X	X	X	X	X	...	...	...	...
12 ID, 2½ wide	25	...	...	X	X	X	X	X	X	...
12 ID, 4 wide	60	...	...	...	...	X	X	X	X	X
16 ID, 4 wide	100	...	...	...	...	X	X	X	X	X
22 ID, 4 wide	150	...	...	...	...	X	X	X	X	X
Barrels										
20 ID, 16 high	250	...	...	...	X	X	X	X	X	X
20 ID, 30 high	500	...	...	...	X	X	X	X	X	X
23 ID, 30 high	750	...	...	...	...	...	X	X	X	X

40% more than any of the first six classes of electrodes shown in Table 1.

There is a lack of agreement among users regarding selection of electrode wires, but in some areas there is reasonably close agreement. For example, E70S-4, E70S-5 and E70S-6 electrode wires have higher total content of deoxidizing elements (manganese, silicon and aluminum) than do E70S-1, E70S-2 and E70S-3, and thus are better suited for use with carbon dioxide shielding gas (see Table 2).

When the shielding gas is largely argon, electrode wires E70S-1 to E70S-3 are suitable. Electrode wire with a composition like E70S-1, which contains the least amount of deoxidizers of any of the classes shown in Table 1, is well suited for welding rust-free work metal in flat and horizontal positions, using a spray-type arc and a shield of argon and oxygen or of argon and carbon dioxide. For out-of-position welding or when the work metal is rusty, electrodes E70S-2 or E70S-3 generally give better results. The E70S-2 and E70S-3 electrodes also are capable of producing sound welds in semikilled or rimmed steel.

When the base metal is not perfectly clean, or when a slightly reactive shielding gas is used, E70S-4 is more suitable because it has a higher content of deoxidizers.

Aluminum-containing electrode compositions, such as E70S-5, are designed for operation at high current density with a spray-type arc, and should not be used with globular-type transfer. When welding is done with an E70S-5 electrode, some rust or mill scale on the work metal can be tolerated without serious impairment of weld quality.

Some plants prefer an electrode composition like E70S-6 because of its versatility. This composition is best suited for use with carbon dioxide shielding gas and works satisfactorily with both a spray-type arc at high current density and a short-circuiting arc at lower current density. (Example 79 describes an application in which improved weld quality was obtained, in part, by changing from an E70S-3 to an E70S-6 electrode wire.)

For better mechanical properties and weld soundness, many prefer a low-alloy steel electrode like E70S-1B. Some plants insist on using this grade for critical welds in low-carbon (mild) steel when carbon dioxide shielding must be used. The "quick-freeze" characteristics of the electrode make it suitable for out-of-position welding.

Emissive electrodes, of the E70U-1 class, have a specially treated surface that enables the electrode to be used with straight-polarity direct current without loss of arc stability. Emissive electrodes are designed to give a spatter-free, spray-type arc, using argon as a shielding gas, and may be used in the flat and horizontal positions for welds on rimmed steel. The use of straight-polarity direct current with these electrodes permits higher deposition rates than those obtainable when reverse-polarity direct current is used.

Composite Electrodes. Although most electrode wires used for gas metal-arc welding are solid, composite wires are available and are sometimes used for welding alloy steel. A composite wire is similar in construction to a flux-cored wire (see the article on Flux-Cored Arc Welding, which begins on page 24), except that the composite wire used for gas metal-arc welding contains a core of metal powder instead of flux. The tubular exterior of the wire is usually of low-carbon steel, and the composition of the powder core is varied as appropriate to produce welds of desired alloy content under specific welding conditions.

A principal advantage of composite electrode wire is that special compositions can be produced economically in small quantities for specialized welding applications.

Selection of Wire Size (Diameter). Standard electrode-wire diameters for gas metal-arc welding are 0.020, 0.025, 0.030, 0.035, 0.040, 0.045, $\frac{1}{16}$ (0.062), $\frac{5}{64}$ (0.078), $\frac{3}{32}$ (0.094), and ⅛ (0.125) in. Usually, there is a size of wire that will yield minimum-cost welds for a specific application. When experience has been gained on an application, a better choice of wire size may be possible.

No rules have been established for the selection of wire size, but the following should be considered when making an initial choice:

1. Melting rate is a function of current density. If two wires of different diameters are operated at the same current, the smaller of the two will have the higher melting rate.
2. Penetration is also a function of current density. If welds made with two different sizes of wire are cross sectioned, the weld made with the smaller wire will show the deeper penetration (other factors being equal).
3. Large wires deposit wider beads than do small wires under identical travel and joint conditions.
4. Stock thickness affects choice of wire size. Fillet and lap-joint welds on sheet metal 0.032 in. thick are usually made with 0.025 or 0.030-in.-diam wire. These wires also work well with stock thicknesses up to about 0.075 in. As the stock thickness increases, the wire size can be increased.
5. Welding position affects choice of wire diameter. Gas metal-arc welding is adaptable to vertical-down operation on stock up to ⅜ in. thick. Wire diameters for welding this thickness can vary from 0.030 to 0.045 in. Butt welds between beveled plates can be made vertically with wires ranging from 0.030 to 0.045 in. in diameter.
6. Penetration-type welds such as arc spot welds require the largest wire possible, to produce the largest interface or nugget diameter.

Available Packages. Electrode wire is packaged on spools, in coils, or in barrels. Table 3 lists the sizes and weights of the types of package in which electrode wire of various diameters is usually available.

Several factors should be considered in selecting the most practical form of package. Almost without exception, the heavier the spool or coil, the lower the price per pound, but some wires, even when sealed in their packages, have a relatively short shelf life, so that carrying excessive stock is inadvisable.

The type of feeder used often dictates the size of wire package. For instance, when self-contained electrode holders are used, the maximum weight of spool is 1 to 2½ lb.

Small spools or coils may be the most economical because of the reduced risk

Table 4. Shielding Gases Used for Gas Metal-Arc Welding

Shielding gas	Welding applications
Gases Inert to Work Metals	
Argon	Virtually all metals
Helium	Aluminum and copper alloys, for greater heat and minimum porosity
75A-25He to 25A-75He	Same as helium, but quieter and more controlled arc
Helium + 10% argon	High-nickel alloys
Gases Reducing to Work Metals	
Nitrogen	Copper; very powerful arc (not used in U. S.)
Argon + 25-30% nitrogen	Copper; powerful arc, but smoother operating and more controlled than arc obtained with nitrogen alone (seldom used)
Gases Oxidizing to Work Metals	
Argon + 1-2% oxygen	Carbon, alloy and stainless steels
Argon + 3-5% oxygen	Carbon steels; alloy and stainless steels, using deoxidizing wire
Argon + 5-10% oxygen	Steel, using a deoxidizing electrode wire
Argon + 20-30% carbon dioxide	Steel, chiefly with short-circuiting arc
Argon + 5% oxygen + 15% carbon dioxide	Steel, using a deoxidizing electrode wire
Carbon dioxide	Carbon and low-alloy steels, using a deoxidizing electrode wire
Carbon dioxide + 3-10% oxygen	Steel, using a deoxidizing electrode wire
Carbon dioxide + 20% oxygen	Steels

of wastage by contamination. When the spool or coil is placed in the unit, it is exposed to the atmosphere, and contamination results. Therefore, containers that can be used up in one or two shifts should be chosen.

In some compositions, barrels that contain from 250 to 750 lb of wire are available (see Table 3). In addition to being lower in initial cost (per pound), barrel packages reduce the amount of downtime required to change wire in comparison with the smaller spools or coils. This can be an important consideration in high-volume production.

Shielding Gases

The primary purpose of shielding gas is to protect the molten weld metal and the heat-affected zone immediately adjacent to it from oxidation and other contamination. Reactive metals such as titanium require protection over a much greater area in the weld vicinity.

Gases Used. Originally, only the inert gases argon and helium were used for shielding, but carbon dioxide is now used extensively, and oxygen and carbon dioxide are often mixed with the inert gases. Chemical behavior and welding applications of the gases and mixtures of shielding gases commonly used in the gas metal-arc process are presented in Table 4.

Argon. Welding-grade argon is 99.995% pure. It is a monatomic gas (one atom per molecule), is inert, and is insoluble in molten metal. Argon is 38% heavier than air, which is advantageous for welding in the flat position and the horizontal fillet position.

As Table 4 shows, pure argon can be used as a shielding gas for virtually all metals, but it is not ordinarily used in welding steels, for which argon-base mixtures are preferred (see "Gas Mixtures", in next column). The use of argon with reverse-polarity direct current when welding plain carbon steel often results in undercutting along the edges of the weld.

Argon shielding results in a bead shape that is different from those obtained with helium or carbon dioxide shielding. Also, under otherwise identical welding conditions, argon shielding results in a different pattern of penetration than carbon dioxide shielding (see Fig. 6).

Argon has a lower ionization potential than helium has, which results in lower arc voltage for a given arc length. Consequently, less heat is produced at a given amperage with argon than with helium, which makes argon preferable to helium for the welding of thin sections. Argon is about ten times as heavy as helium, so less argon is required to retain a protective blanket over the weld area in the flat position and the horizontal fillet position.

Argon costs less than helium (per unit of volume purchased) and is more plentiful in supply, which partly accounts for its being used far more extensively than helium.

Helium also is inert and monatomic, but because it is only 14% as heavy as air, a greater volume of helium is required to equal the amount of shielding provided by argon for welding in the flat position and the horizontal fillet

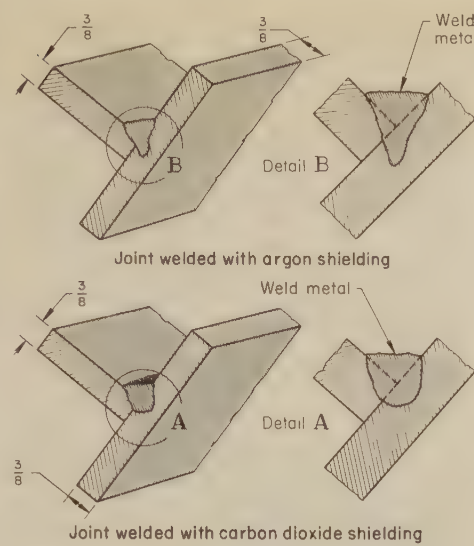


Fig. 6. Patterns of penetration obtained using argon shielding and carbon dioxide shielding in flat-position fillet welding under otherwise identical conditions

position. Higher cost and limited supply have also limited the use of helium as a shielding gas.

Helium shielding results in a higher arc voltage for a given arc length and amperage than that obtained with argon shielding. Consequently, more heat is produced at any given amperage with helium. This characteristic (due to high ionization potential) makes helium preferable for use in welding thick sections and highly conductive metals.

Carbon Dioxide. Most reactive gases cannot be used alone for shielding. Carbon dioxide is the outstanding exception; it is extensively used both by itself and as a component of gas mixtures, to which it imparts improved arc action and metal transfer.

Carbon dioxide has become widely used in the welding of steel by the short-circuiting mode of metal transfer. A true spray arc is not obtained with a shielding gas composed entirely of carbon dioxide. In many applications, carbon dioxide has provided good welding speed and good penetration, and in many applications the welds so shielded have proved to be less expensive than argon-shielded welds.

Carbon dioxide decomposes to carbon monoxide and oxygen at arc temperatures, producing an oxidizing effect approximately equal to that obtained by the use of an inert gas with 8 to 10% oxygen. In spite of this oxidizing effect, sound weld deposits, free of porosity, can be consistently obtained with carbon dioxide shielding when a deoxidizing electrode wire is used with the globular mode of metal transfer.

The major disadvantage of carbon dioxide shielding is that it produces a "harsh" arc, which is likely to make metal transfer somewhat spattery. Weld spatter can be minimized by maintaining a short, uniform arc length.

Gas Mixtures. Often, the advantages of two or more gases can be utilized by mixing them. Common mixtures include argon with helium, argon with oxygen, argon with oxygen and carbon dioxide, and carbon dioxide with oxygen. Some typical proportions are given in Table 4. Mixtures of argon with chlorine or with nitrogen are less frequently used.

Although the pure inert gases are capable of protecting metals at any temperature, they are not suited to all welding applications. By introducing controlled quantities of reactive gases and mixing them with the pure inert-gas shield, improved arc action and metal transfer can be obtained, without degrading the effectiveness of the shielding gas.

Additions of oxygen or carbon dioxide to inert gases help to stabilize the arc, to promote favorable metal transfer, and to minimize weld spatter. At the same time, they change the penetration pattern and promote wetting and flow of the weld metal along the fusion edges in the welding of plain carbon and low-alloy steels, thereby either preventing or substantially reducing undercutting.

The addition of only a small amount of oxygen or carbon dioxide to an inert gas will produce an appreciable change in arc action and metal-transfer characteristics. Additions of 1 to 5% oxygen are the most common, although even ½% oxygen will produce a noticeable change. Oxygen and carbon dioxide are sometimes added to either helium or mixtures of argon and helium, for welding of alloy and stainless steels, when the short-circuiting mode of metal transfer is used.

The addition of oxygen or carbon dioxide to argon causes the gas to become oxidizing, which results in weld porosity in some ferrous metals. To prevent this, electrode wire used in welding with a shielding-gas mixture containing oxygen or carbon dioxide must contain deoxidizers to counteract the undesirable effects of the oxygen on the metal.

Gases used with a short-circuiting arc often differ from those most commonly used with a spray-type arc. For example, mixtures of argon with 20 to 30% carbon dioxide are frequently used with short-circuiting arcs, but are seldom used with spray-type arcs. However, when welding with a short-circuiting arc, almost any gas or gas mixture that is suitable for use with a spray-type arc can be used.

Cost of any given shielding gas per unit volume depends greatly on the amount purchased at one time and on the type of container in which it is received (see the section on Supply and Storage of Shielding Gases, which follows). Geographical location and factors of sales competition also influence cost markedly. Nevertheless, for a given volume of gas purchased under the same conditions, helium is the most expensive, argon is next, and carbon dioxide is the least expensive.

Cost of the completed weldment is the significant figure, so that whether or not the use of a less expensive shielding gas reduces the cost of the weldment depends on whether other processing costs are consequently increased or decreased.

In the example that follows, the use of a lower-cost shielding gas required premium-quality electrode wire and decreased electrode speed; this increased the direct cost of the weldments.

Example 78. Effect of Shielding Gas on Total Cost of Weldments (Table 5)

A cost study was made to evaluate the effects of two different shielding gases (carbon dioxide versus argon plus 5% oxygen) on total direct cost of making two 3⁄16-by-6-in. fillet welds on a 1040 steel farm-implement part (see illustration in Table 5).

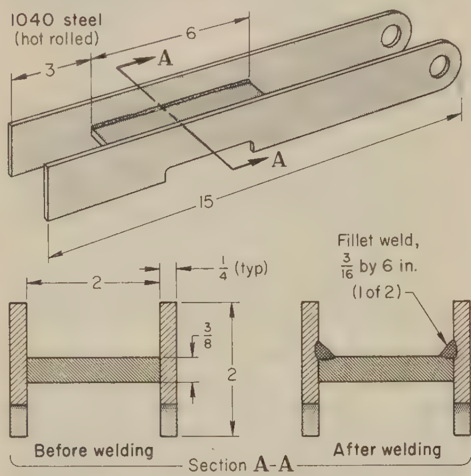
Welding conditions and cost figures for making the welds with the two shielding gases are compared in Table 5. The costs given show that welding cost per 100 parts was 13.6% lower when argon plus oxygen was used, even though this gas mixture cost 2.7 times as much as carbon dioxide. The reasons for this were: (*a*) a high-strength, premium-price electrode wire had to be used with carbon dioxide shielding gas to maintain the weld quality obtained with the argon-oxygen mixture; and (*b*) electrode speed was less with carbon dioxide shielding, which increased labor cost.

Selection of a shielding gas for a given application depends on the type and thickness of the base metal, cost and effectiveness of the different gases, joint design, position of welding, technique to be employed, fixturing, speed and required quality.

There are no strict rules that govern the selection of shielding gas. For instance, in Example 78, use of argon plus oxygen instead of carbon dioxide resulted in a lower-cost weldment. Conversely, in the example that follows, in an entirely different type of operation (different plant, automated welding, and different quality requirements), carbon dioxide proved superior to an argon-oxygen mixture — providing higher-quality welds at greater speed.

Table 5. Effect of Type of Shielding Gas Used on Cost of Welding a Farm-Implement Part (Example 78)

Item	Type of shielding gas(a) Carbon dioxide	Argon plus 5% oxygen
Cost per Hundred Weldments		
Labor	$2.76	$2.19
Shielding gas	0.31	0.83
Electrode wire	2.50	1.79
Total	$5.57	$4.81
Welding Conditions(b)		
Size of electrode wire, in.	0.047	0.045
Type of electrode wire	(c)	(d)
Deposition rate, lb per hr	10.3	11.9
Gas flow, cfh	30	24
Wire-feed rate, ipm	350	440



(a) Both types of shielding gas were purchased in cylinders. (b) Power supply for welding with both shielding gases was a 500-amp constant-voltage three-phase rectifier equipped with variable slope control; electrode holder was water cooled. (c) High-strength, premium-price wire was used to avoid fusion-zone porosity and cracking. (d) Low-carbon steel.

Example 79. Change of Shielding Gas for Improved Quality and Productivity in Automatic Welding of Compressor Housings (Fig. 7)

Originally, 1020 steel compressor housings (see Fig. 7) were welded by the gas metal-arc process with a shielding gas composed of 98% argon and 2% oxygen. The two components of the housing assembly were clamped manually to a rotating positioner and were welded with a machine-held electrode holder fed with 1⁄16-in.-diam E70S-3 electrode wire. When the weldments were tested with a Freon leak-rate detector, rejection rates averaged 7%. Leaks were caused by porosity, incomplete fusion, and misdirected welding arcs. With this technique, welding speed was 45 in. per minute, and average production rate was 30 weldments per hour.

In an effort to improve quality and production rate, plasma-arc welding was considered, but was ruled out because of excessive spatter on the interior wall of the housing. Electron-beam welding was also considered, but it achieved a welding speed of only 12 in. per minute because of the oscillating technique required for bridging the cross section of the joint to attain adequate weld strength; in addition, the initial cost of equipment for electron-beam welding was very high. Flux-cored arc welding was rejected because of the necessity for removing slag, and because of the higher cost of filler metal (compared to the cost of 1⁄16-in. solid wire).

Finally, a dual-head gas metal-arc welding machine was built to replace the original equipment. The new machine included a three-phase transformer-rectifier with a rating of 500 amp at 100% duty cycle, a heavy-duty wire-feed unit with dynamic braking, a custom-built electrode holder and mounting fixture with a mechanical tracking device, automatic V-clamping jigs, and a variable-speed rotating head — all integrated into one machine.

With the new equipment, using the same shielding-gas mixture, electrode wire, and welding speed as in the original method, production rate was increased to 60 weldments per hour. Although the rejection rate was reduced to 5%, that was unacceptably higher than the 3% rejection rate considered reasonable.

Rejection rate was reduced to less than 2% by changing the shielding gas to carbon dioxide (obtained from dry-ice converters) with a dew point of −60 F, and by changing from E70S-3 to E70S-6 electrode wire. The E70S-6 wire provided a weld bead of better shape, and was able to tolerate a greater amount of base-metal surface impurities, such as oil and drawing compound. Welding conditions for the final improved method are given in the table that accompanies Fig. 7. The only new requirement was that the maximum root opening during fit-up had to be held to 0.040 in. (see section A-A in Fig. 7), instead of 0.060 in. as originally specified.

With the carbon dioxide shielding gas, welding speed was doubled, to 90 in. per minute, and weld spatter was barely detectable. As a result, production — from assembly of components through unloading of the welded units — rose to an average of 120 weldments per hour. In addition, the cost of the carbon dioxide was only 9% of the cost of the argon-oxygen mixture, which resulted in a saving of $9000 per year on shielding gas.

Chemical behavior and suggested uses of 15 different shielding gases and gas mixtures are summarized in Table 4. The suggested uses are based on experience with a variety of applications. In some applications, more than one gas or gas mixture has proved satisfactory for a specific metal or set of welding conditions, which indicates that there can be considerable flexibility in the selection of a shielding gas.

In a given plant, every attempt is made to standardize usage of shielding gases so that a minimum number is purchased and a minimum number of mixtures is used. Thus, the range of applications in a particular plant influences the choice of shielding gas.

Other considerations in selecting a type of shielding gas are:

1. Total amount of gas used during a specific period of time
2. Peak demand
3. Consistency of use and length of periods of nonuse
4. Portability of gas containers.

(See also "Shielding Gases" for gas tungsten-arc welding, pages 122-124.)

Supply and Storage of Shielding Gases

Except for portable banks, bulk supply units for shielding gases should be located outdoors (preferably protected from the weather), and away from flammable materials and from buildings and personnel. The site should meet insurance and local code requirements.

Advantages of bulk supply include:

1. Operating pressures are selected by the user and are regulated from a central control unit.
2. The gas supplier checks and services bulk units.
3. Work areas are free from cylinders.
4. The need for trucking cylinders and changing regulators is eliminated.

Portable Bank Supply. In this system, portable banks of cylinders (usually 12) are connected to a duplex manifold header that is normally provided with an automatic control unit. When the operating side of the manifold is exhausted, this control unit cuts in the reserve side to maintain gas supply to the distribution pipeline. The cylinders are mounted in a cradle provided with swivel casters and a crane hook.

A typical portable bank supply is 6 ft, 5⅝ in. high over-all, 3 ft, 1⅞ in. long, and 2 ft, 4½ in. wide; weighs 2000 lb empty and (depending on the type of gas contained) about 2300 lb filled; and has a capacity of 3180 cu ft of helium at 2400 psi and 70 F or 4008 cu ft of argon at 2640 psi and 70 F.

Trailer-storage supply of shielding gas involves the use of a mobile trailer, a stationary storage unit, and an automatic pressure-reducing control. Space is normally provided for two trailers and an adjacent stationary reserve storage unit. One trailer is on the property at all times. The second space allows delivery of a replacement trailer prior to removal of the empty trailer. The reserve storage unit automatically supplies gas to the distribution piping system when the trailer is exhausted. The gas is automatically replaced in the stationary reserve storage unit when a full trailer is delivered and connected to the control unit.

Tow trailers are two-wheeled units usually containing 26 manifolded cylinders (capacity of each cylinder, approximately 400 cu ft), and are normally towed by a regular cylinder-delivery truck. A 26-cylinder tow trailer can

hold 11,583 cu ft of argon (2640 psi, 70 F) and 9,157 cu ft of helium (2400 psi, 70 F), and requires a space of 14 by 35 ft.

Tube trailers are semitrailer units containing 30 or more manifolded 20-ft tubes, and are usually transported by a standard tractor. A tube trailer with 30 tubes can hold 45,148 cu ft of argon (2640 psi, 70 F) and 38,950 cu ft of helium (2400 psi, 70 F), and requires a space of 25 by 35 ft.

The reserve storage unit consists of manifolded cylinders or storage tubes. Cylinders are normally used for argon, and 12-ft tubes are used for helium. The control unit incorporates two regulators, set differentially by approximately 10 to 15 psi.

Bank-fill supply of shielding gas requires high-pressure gas systems consisting of storage and control units. Manifolded cylinders are normally used for argon, and tubes for helium. Each cylinder has a capacity of 245 cu ft of argon at 2200 psi and 70 F.

The storage unit is separated into an operating and a reserve section. The reserve section is available in emergency and is also used for supplying the distribution pipeline during recharging of the operating section. Recharging is done from mobile delivery equipment. The quantity of gas delivered is computed from the volume at standard conditions before and after filling.

The control unit consists of valves, gages and regulators for filling the operating and reserve sections and for delivery of the gas to the distribution system. Space requirements, including allowance for control units, are:

72 cylinders	11½ by 16 ft
108 cylinders	11½ by 21¼ ft
144 cylinders	11½ by 26½ ft
180 cylinders	11½ by 31¾ ft
12-ft tubes, std unit	14½ by 21¼ ft

Additional space of approximately 12 by 32 ft (preferably concrete) is needed for parking the delivery unit.

Liquid-converter bulk supply units store gas in liquid form, vaporize the liquid, and deliver gas to the pipeline at a constant pressure. The complete unit consists of a storage tank with control cabinet, a vaporizer and a fill-connection stand.

Each gas manufacturer has its own standards for converter sizes to handle all demands. The following sizes of converters are available at the indicated maximum delivery flow rates (rated capacities given below are for liquid oxygen; capacities for liquid argon would be slightly higher):

Capacity, scf	Delivery, scf/hr
35,000	500 continuous, 1500 intermittent
65,000	1500 continuous, 3000 intermittent
100,000	10,000
250,000	30,000
500,000	60,000

Standard converters can be modified to increase delivery rates. Custom units are designed to handle any load. Delivery pressure for a converter system is normally limited to 175 psi. Converter storage units having capacities of 35,000, 65,000 and 100,000 cu ft have integral atmospheric vaporizers; those with capacities of 250,000 and 500,000 cu ft require separate vaporizers. Atmospheric vaporizers use atmospheric heat; electrical vaporizers use electrically heated water. Standard atmospheric vaporizers are available with continuous flow rates of 2000, 4000 and 6000 scf per hour; electrical vaporizers (220/440 volts, three-phase), are available with continuous flow rates of 8000 scf per hour (30 kw) and 16,000 scf per hour (60 kw).

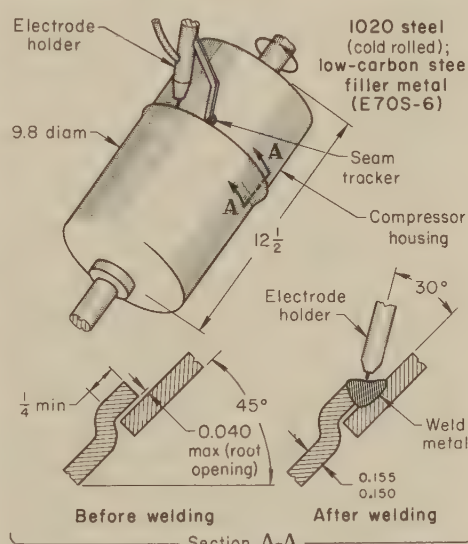
A liquid-converter supply unit provides the arrangement of related equipment best suited for operation, maintenance and delivery to the unit. Filling is accomplished for liquid-delivery equipment through meters, which measure the volume of liquid.

A clean concrete area with protective fencing is required for the liquid converter. The area requirements range from a minimum space of 8 by 8 ft to a maximum of 18 by 20 ft. A hard-surface unloading area at least 12 by 45 ft adjacent to the unit is also required.

Bulk Carbon Dioxide Storage. When a number of welding stations are involved but total usage of carbon dioxide is low, banks of cylinders are located in a suitable area and the gas is piped to the various stations. The banks of cylinders are arranged so that a group of manifolds feeds gas to the main header. Each manifold is attached to a bank of cylinders (14 or 16) and can be turned off independently of the other manifolds. Gas is taken from one or two banks until the pressure in the bank or banks drops to the established minimum delivery pressure. Then the gas source is manually switched to another bank of cylinders. When the last bank of cylinders is being used, the supplier should be notified so that all cylinders can be replenished.

The gas passes through a vapor heater on the main header and is then regulated with a flowmeter to proper flow pressure at the welding stations.

When enough carbon dioxide is used to warrant a low-pressure bulk storage system, a storage tank equipped with a vaporizer is located in a central area that is practical both for filling the storage tank from delivery trucks and for piping the gas to the various welding stations. Piping should be of adequate size and of proper strength to transmit the gas at tank pressure to the stations and to supply all stations with the required volume of gas. A minimum line size of ⅝ in. is recommended. Both one-step and two-step regulation are available. In one-step regulation, tank pressure is carried in the vapor-supply header to the work station, where it is regulated to the proper pressure. In two-step regulation, pressure is regulated at the bulk storage tank to approximately 100 psi, and then is regulated to the proper operating pressure at the station. A regulator is required at each station, and a flowmeter should be installed to control flow rate to the electrode holder. A typical bulk carbon dioxide storage system comprises the following:



Conditions for Gas Metal-Arc Welding With Less Than 2% Rejections

Joint type	Lap
Weld type	Fillet
Power supply	500-amp rectifier(a)
Electrode wire	$\frac{1}{16}$-in.-diam E70S-6
Electrode holder	600 amp, water cooled(b)
Fixtures	Clamping jig, rotating positioner
Current	450 to 475 amp, dcrp
Voltage	32 to 34 v
Shielding gas	Carbon dioxide(c); 60-70 cfh
Welding position	Flat
Number of passes	One
Wire-feed rate	380 ipm
Stickout	¾ to 1 in.
Travel speed	90 ipm (2.9 rpm)
Production rate	120 housings per hour

(a) Constant-voltage type with wire-feed unit. (b) Custom built. (c) Dew point, −60 F max.

Fig. 7. Orientation and joint design for automatic welding of a compressor housing under the conditions listed in the table, which increased production and reduced rejections in comparison with previous methods (Example 79)

1 **Pressure Vessel.** This is a cylindrical steel tank, built to conform with the ASME Code for Unfired Pressure Vessels, designed for a working pressure of 363 psi and tested during manufacture by hydrostatic and vapor-pressure tests applicable to the code.

2 **Insulation.** Not less than two layers of 4-in.-thick blanket-type insulation must surround the vessel, to provide high thermal efficiency. Insulation is securely held in place to prevent moving, sagging or cracking. Normally, no downtime is required for maintenance of insulation.

3 **Housing.** The entire storage unit (in sizes up to 12½ tons) is enclosed in a welded, sheet steel housing mounted on a rigid channel iron base. The housing is hermetically sealed, and the exterior is finished in high-grade enamel to facilitate keeping it clean and sanitary.

4 **Refrigeration.** This is provided by a ruggedly built compressor and refrigeration coil running lengthwise through the pressure vessel near the top. A pressure switch starts the compressor whenever the pressure of the carbon dioxide reaches approximately 305 psi, and stops it when pressure drops to about 295 psi.

5 **Vaporizer and Vapor Heater.** These devices ensure a constant supply of vapor at uniform pressure. The vapor heater also ensures maximum economy in carbon dioxide consumption.

6 **Safety Devices.** The storage unit is fully protected against abnormally high tank pressures, which can result from prolonged compressor operation or power failure, by multiple safety devices. These include a bleeder relief valve that opens at 341 psi, two safety pop valves that open at 357 psi (a two-way switching valve makes it impossible to shut off both safety pop valves simultaneously), and a frangible disk normally connected to a line venting to the outside of the building.

In addition, an alarm sounds automatically if pressure rises to approximately 325 psi, or falls below approximately 275 psi.

7 **Liquid-Level and Pressure Gages.** These gages show carbon dioxide quantity and pressure, and are located on the front of the storage unit.

Liquid carbon dioxide is pumped into the storage unit through the fill line that extends from the side of the tank. No interruption or shutdown of normal operations is necessary during refilling.

The liquid carbon dioxide from the storage unit is passed through a thermostatically controlled vaporizer engineered to provide the volume of vapor the system will normally be required to produce. Automatic controls maintain pressure within predetermined limits. The carbon dioxide vapor is piped back to the tank, where a reservoir of vapor is maintained constantly. From the vapor space in the storage unit, the gas is piped through a filter and a vapor heater to the welding station. Such a system ensures an automatically regulated supply of carbon dioxide gas, even under the heavy demand of peak loads.

Storage units with capacities of 1 to 12½ tons are the sizes most frequently used in bulk liquid carbon dioxide systems, although there is no recognized limitation to the size of a storage unit. Electrical requirements are as follows:

1 All storage units require 1 kw, 110 volts, 60 Hz for the alarm circuit.
2 When vapor is used from the tank with an electrical vaporizer, 12 kw, 220 or 440 volts, 3-phase is required.
3 When vapor is used from the tank with a steam vaporizer, 3 kw, 220 or 440 volts, 3-phase, 60 Hz is required.

Liquid-argon cylinders contain approximately 3000 cu ft of argon gas, and may or may not be classified as bulk-type supply systems. These cylinders have definite limitations on maximum withdrawal rates and desired pressures. They may be manifolded together with an operating side and a reserve side, with a central control-cabinet arrangement.

Cylinder manifolds are recommended where gas volume is insufficient to warrant bulk supply units. Cylinder manifolds provide a centralized location of gas supply for distribution by pipeline. Manifolds may be simplex (one header) or duplex (two headers). Control units may have a single regulator, may be manual with dual regulators, or may be automatic with dual regulators. Manifold installations must be approved by insurance inspectors and must meet NFPA standards 51, 565 and 566.

Equipment for Gas Control

Regardless of the type of gas-supply system used, constant pressure and flow of the gas must be maintained. The main functions of a regulator are to reduce pressure from the source to a working pressure, and to maintain a constant delivery pressure regardless of variations at the source. In addition, a regulator must be adjustable to deliver gas at a certain desired pressure within its rated range. Regulators are broadly classified into four main types: single-stage nozzle regulators, single-stage stem regulators, two-stage nozzle or stem regulators, and line regulators.

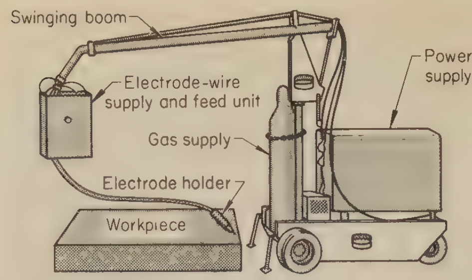


Fig. 8. Self-contained portable unit for on-location gas metal-arc welding

Single-stage nozzle regulators consist of a brass casing, an adjusting screw, springs, a diaphragm, a nozzle and a seat. When the adjusting screw is turned clockwise, the seat is forced away from the nozzle, allowing the gas from the cylinder to enter the working-pressure chamber. This increases the pressure on the diaphragm, which forces the seat closer to the nozzle. In this manner, the regulator mechanism arrives at a balance of forces and the amount of gas withdrawn from the working-pressure chamber is replaced, which keeps pressure constant.

Inlet pressure exerts additional force against the seat member in the opening direction away from the nozzle. This force varies according to the area of the seat. The outlet pressure decreases somewhat as the inlet pressure decreases, because the force acting to move the seat member away from the nozzle is reduced as the inlet pressure decreases. Therefore, a lower outlet pressure on the underside of the diaphragm will close the seat member against the nozzle. The opening between the seat member and the nozzle is thereby reduced, resulting in decreased gas flow.

Single-stage stem regulators operate like the nozzle type, except that the high inlet pressure acts to hold the seat against the nozzle, instead of away from it as in the nozzle type. Therefore, as the inlet pressure drops, the outlet pressure increases somewhat as the cylinder pressure goes down. This increase is caused by a decrease of the force produced by the gas pressure against the seating area. Stem and nozzle regulators reduce gas pressure and are similarly adjusted.

Two-Stage Regulators. In two-stage pressure reduction, the high-pressure gas initially passes through an essentially nonadjustable nozzle or stem assembly. This assembly, equipped with a heavy diaphragm and spring, reduces pressure to an intermediate value. Further pressure reduction is accomplished by passing the gas through a second-stage regulator of either the stem or the nozzle type, which is adjusted to give the desired outlet pressure. Two-stage regulation provides a more nearly constant delivery pressure than is obtained by single-stage regulation. A two-stage regulator will give constant delivery pressure from a full cylinder down to the pressure setting of the first stage. From there on until the cylinder is empty, the first stage remains open and is inactive, insofar as any regulation is concerned, and gas pressure is regulated by the second stage only.

Line regulators can be of either the stem or the nozzle type. They are designed to receive inlet pressures not greater than 500 psi, and are used at welding stations that are fed by a pipeline system containing gas already reduced to an intermediate pressure at the source of supply. For this reason, line regulators are single-stage, and one is required at each welding station.

Application of Regulators. Regulators are available for almost any required pressure and capacity. When gases are supplied from single cylinders, a capacity of 120 cu ft per hour is usually sufficient. When gas cylinders are manifolded, or when a bulk system is used, regulators having capacities as high as 40,000 cu ft per hour may be required. Station regulators in distribution lines are normally low-pressure line regulators available in various sizes to meet the demands of a particular station.

When large-volume distribution lines are used, two-stage regulators are desirable at the source of supply. Total capacity should be more than the total usage of all line stations. Single-stage or two-stage regulators can be used for single-cylinder installations. The single-stage type is commonly used because it costs less than the two-stage type.

Premixed Gases. Commonly used mixtures of gases, such as argon with 1% oxygen and argon with 2% oxygen, are easily obtained premixed, and unusual mixtures can be obtained premixed at reasonable cost if quantities are large enough. The use of premixed gases minimizes handling of cylinders and the need for flowmeters and regulators.

Mixing Argon and Carbon Dioxide. Proportioners are available to mix argon and carbon dioxide with an accuracy of ±1% at flow rates ranging from 1 to 1000 cu ft per hour. An indicated-maximum-time proportioner operates on the surge-tank principle, filling the tank to a predetermined pressure. Then, as the pressure drops from usage, the proportioner refills the tank.

The controls, which require little space, are built on top of the tank. Special controls eliminate the possibility of leakage. Once the gases are mixed, the unit maintains line pressure between 40 and 45 psi, when operating from a 55-psi source of supply. A recording analyzer can be incorporated.

Mixing Argon and Oxygen. Equipment used for mixing argon and oxygen comprises one argon regulator and flowmeter, and one oxygen regulator and flowmeter, with a connecting Y. To adjust the mixture:

1 Connect the argon and oxygen regulators, and tighten them to the cylinder valves.
2 Connect the argon and oxygen flowmeters, position them vertically, and tighten.
3 Adjust the argon and oxygen regulators to equal delivery pressures (25 psi minimum).
4 Adjust the argon flowmeter to the desired flow rate.
5 Adjust the oxygen flowmeter to the desired flow rate.

Argon and carbon dioxide can also be mixed, using an argon and carbon dioxide regulator with flow meters connected to a Y-connector.

Each of the flowmeters is adjusted with the needle valve at the base of the

meter. When adjusting the flowmeters, it is necessary to open the control valve or to disconnect the hose at the base of the Y. It is important that both regulators be adjusted to an equal pressure of not less than 25 psi.

Cylinder and regulator connections for different gases are of different sizes and shapes to eliminate the possibility of a mismatched regulator and cylinder. The Compressed Gas Association has formulated a complete set of specifications for noninterchangeable cylinder valves and regulator inlet connections. Regulators should be used only for the service for which they were designed.

Regulator outlet fittings differ in size and thread, depending on the size and capacity of the regulator.

Flowmeters control the rate of gas flow. They may be designed and calibrated for a specific gas, although some flowmeters are available that have several calibrated scales and can be used for different gases. The scale on shielding-gas flowmeters is marked in cubic feet per hour, and flowmeters are available that will handle up to 200 cu ft per hour. With most flowmeters, gas flow is controlled by a valve on the outlet side and is read by movement of an indicator in a calibrated glass tube. Flowmeters can be purchased separately and attached to a regulator, or a regulator and flowmeter can be purchased as an assembly called a flowmeter-type regulator. Ordinarily, the flowmeter is attached to the outlet of the regulator. Flowmeter gas-inlet pressure is specified by the manufacturer, and the regulator must be adjusted accordingly to ensure accuracy of the meter. On flowmeter-type regulators, the pressure can be set and locked, and further adjustment is necessary only after repair. Both one-stage and two-stage regulators can be used. Because of the constant pressure obtained by using two-stage regulators, a more accurate reading may be expected than when using one-stage regulators.

Flowmeters are similar in design but they differ in the method adopted to adjust the flow. In the types previously described, the gas-control valve is on the outlet side of the meter. Some manufacturers eliminate this valve and control the flow by changing the pressure of the regulator. However, the valve-adjustment type is more common in welding applications.

Selection of Regulators and Flowmeters. In selecting regulators and flowmeters, the volume of gas per unit of time required at the electrode holder is the most important consideration. The following may be used as a guide:

1 Select equipment of adequate capacity.
2 If possible, standardize on one make, to simplify maintenance.
3 Select regulators having filters in the inlet connections.
4 Select flowmeter-type regulators for welding stations.

Care of Regulators. Regulators are precision instruments and should be treated as such. By observing the following, long periods of service, with minimum maintenance, can be expected:

1 Clean cylinder valve outlets with a clean cloth, and open valve momentarily, in order to blow out dust, before attaching regulator to cylinder.
2 Release regulator adjusting screw counterclockwise before opening cylinder valve.
3 Open cylinder valve slowly. A sudden surge of high-pressure gas can damage regulators.
4 Use a correct-size wrench (not a pipe wrench) to connect regulator to cylinder, and never force a connection.
5 When checking for leaks, use a grease-free soap-and-water solution.
6 Never use oil or grease on regulators. Only a lubricant approved by the manufacturer should be used.
7 Never use a regulator for other than its specified purpose. Slight traces of oil or dirt in an oxygen regulator can cause a violent explosion.
8 Allow maintenance of regulators to be performed only by qualified personnel using specified parts.

Prevention of Gas Loss

Loss of shielding gas occurs mainly from one or more of three causes: (*a*) use of excessive amounts in welding, or in preparing to weld or to stop welding, (*b*) leaks in gas lines, and (*c*) overfilling the storage unit in bulk systems.

The first cause of loss usually can be corrected by teaching welders that excessive flow of shielding gas results in turbulence and reduced coverage, and wastes gas.

Overfilling of bulk storage units is often the cause of large losses in bulk systems — especially units containing argon, which boils at approximately −300 F. Often, to reduce the frequency of trips, delivery men fill the units to seven-eighths capacity instead of a maximum of three-fourths. This practice may not cause losses during winter months, or when usage is heavy and reasonably constant. However, if the unit is nearly full there is little room for a head of gas, and during a shutdown (for instance, over a weekend), especially in hot weather, the safety valve will open and gas can be lost.

Under no circumstances should an argon storage unit be filled to more than three-fourths capacity. If a lengthy shutdown is expected, the gas supplier should remove some of the liquid argon and keep it until needed.

In a single year, one large plant saved almost $80,000 by correcting the causes of gas loss discussed above.

Equipment Installations

Type and size of equipment, number of welding stations, available space, workpiece size, and number of similar workpieces to be welded influence location and installation of equipment.

Support equipment required for the apparatus used in gas metal-arc welding is considerably more elaborate than that needed for shielded metal-arc welding. In shielded metal-arc welding, all that is required is that electric power (and sometimes water) be supplied to the welding station. In contrast, a power supply weighing from 350 to 1800 lb, gas cylinders weighing from 60 to 150 lb each, a wire supply, and sometimes a tank that holds 30 to 40 gal of cooling water may be needed for gas metal-arc welding. Compact units with swivel booms can be used to increase the area in which welding can be done without moving the main unit.

If welding is done within a relatively small area, the wire-feed motor can be suspended from a column-mounted jib boom. The boom should be equipped with a trolley suspension hook or a small hoist to permit loading of the electrode wire at floor level, and suspension hooks to prevent the power cables and hoses from dragging and tangling.

Portable Units. For many applications, portability of equipment is required. Figure 8 illustrates a portable "package" unit that can be quickly transported for on-location welding. In this unit, both the power supply (engine-driven direct-current generator) and the gas supply are mounted on a truck equipped with a boom that supports the electrode-wire feed and supply, cables, hose and electrode holder. The gas cylinder must be secured at all times, to prevent it from falling.

Typical Stationary Installations. Three types of installation employing swinging booms are illustrated in Fig. 9. Fig-

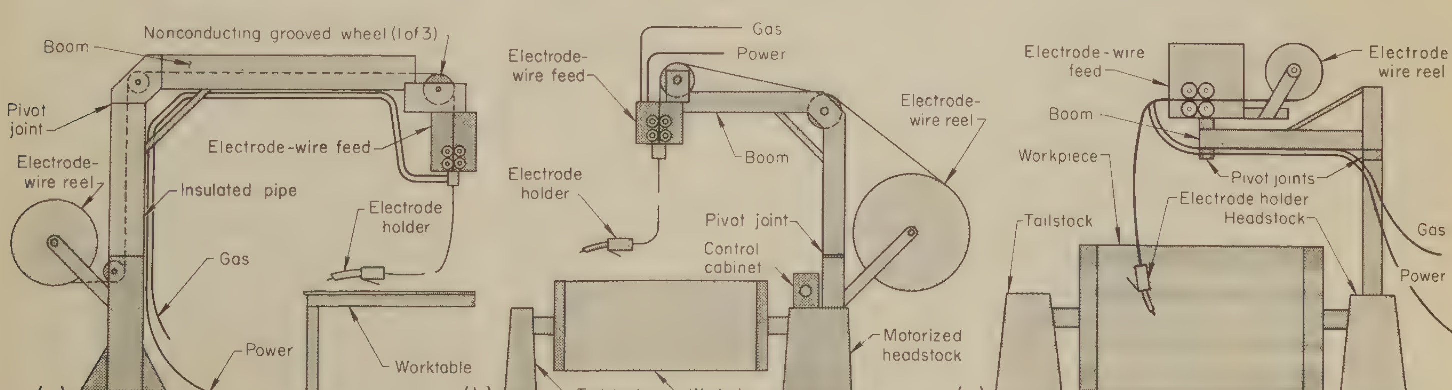


Fig. 9. Three types of swinging-boom installations for gas metal-arc welding. See text for discussion.

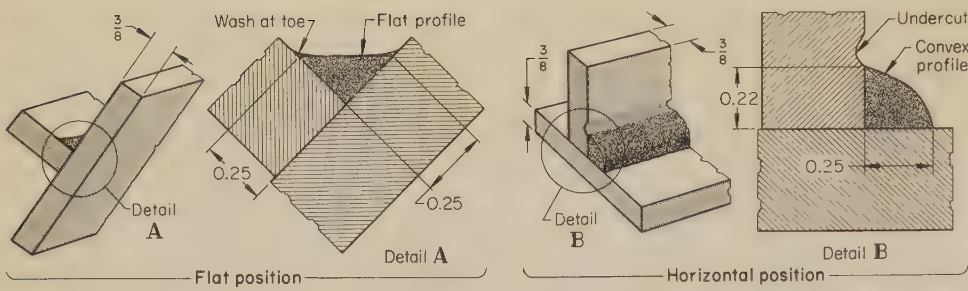


Fig. 10. Comparison of profiles and leg lengths of fillet welds made in the flat position and the horizontal position. Note undercut above horizontal-position weld.

ure 9(a) shows a typical stationary installation that is particularly well-adapted to gas metal-arc welding. The wire-feed mechanism is a considerable distance away from the wire-supply reel. The wire-supply location permits use of large coils of wire. Power and gas supplies are remotely located. The pivot joint permits welding to be performed over a considerable area.

The installation shown in Fig. 9(b) includes a positioner with a motorized headstock, which is helpful for welding massive workpieces; in other respects, this installation is similar to the type shown in Fig. 9(a).

In the installation shown in Fig. 9(c), the electrode-wire reel and the wire-feed mechanism are mounted close together on the end of the boom. Major disadvantages of this arrangement are height of the wire supply and weight on the boom. Extra weight on the boom requires a larger boom and hence higher initial cost. Height of the wire supply above the floor can be a hazard for the operator when reloading wire coils or reels. The rotary positioner used with this installation is not motorized.

Cables and hoses should be kept as short as possible and should not be looped in coils when the welding operation is close to the power supply. Looped coils of welding conductors, functioning as reactors, change the characteristics of the power supply and adversely affect arc operation. Long hoses and cables are susceptible to tangling and kinking, which may cause a restriction in gas or water flow, hence overheating of electrode holders, or porosity in the weld. Long power cables also cause a voltage drop between the arc and the power supply. Large power cables and ground cables are recommended for any installation. The ground cable from the power supply should be securely attached to the workpiece. The use of structural steel and casual bar-stock welding links, or bridges, between numerous weldments is not recommended because they cause voltage drop and stray arcing.

Water-Cooling Systems. Apart from permitting the use of lighter-weight electrode holders and considerably less copper in the power lead, and decreasing the difficulty of removing weld spatter, water cooling adds to the service life of the welding equipment. Proper design, installation and preventive maintenance have largely eliminated the corrosion and plugging at one time associated with gas metal-arc equipment. Sealed recirculating water-cooling systems are preferred, because they enable corrosion to be stopped by the use of inhibitors, and because dirt particles that normally plug small water passages settle to the bottom of the tank. Tap water can be filtered, but this does not remove materials that cause corrosion, and water conditioning is usually too expensive to be considered. Another advantage of sealed systems is that they do not cause the condensation that results from the use of low-temperature tap water.

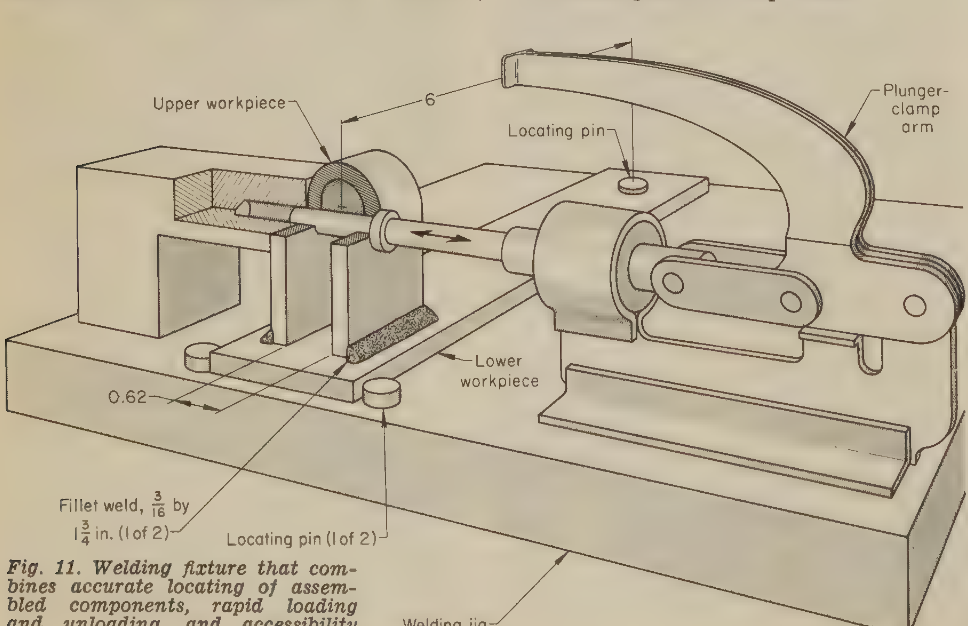


Fig. 11. Welding fixture that combines accurate locating of assembled components, rapid loading and unloading, and accessibility

Holding and Handling Workpieces

Requirements for jigging or fixturing for gas metal-arc welding are usually based on the same considerations as those for other arc welding processes, especially when the electrode holder is hand guided. For additional information on jigging, fixturing and positioning, see pages 11 and 12 in the article on Shielded Metal-Arc Welding, and page 126 in the article on Gas Tungsten-Arc Welding.

Full automation can be achieved in gas metal-arc welding by the use of appropriate fixturing. The continuity of operation that can result from the use of an electrode of virtually unlimited length enables the use of turning rolls and the mounting of electrodes on carriages, and the high welding speeds attainable result in much less heat transfer to the base metal than occurs in the shielded metal-arc and submerged-arc processes. This, in turn, calls for a comparatively small amount of clamping to prevent distortion.

Fixturing for welding in the flat position is generally the simplest and most economical for relatively small weldments. Fillet welds made in the flat position are usually more uniform, less likely to have unequal legs and convex profiles, and less susceptible to undercutting than fillet welds made in the horizontal position (see Fig. 10).

Fixtures for gas metal-arc welding should be designed and built so that locating, clamping and gaging permit good joint accessibility. Fixtures with few protruding clamp arms and gage points allow easy manipulation of the electrode holder.

Figure 11 shows a simple well-designed fixture used in the welding of relatively small parts. By one movement of the plunger-clamp arm, the U-shape workpiece can be secured in position, or the welded assembly can be removed. With minor modifications, the same fixture can be used to weld several different sizes of the same assembly.

Small-diameter (under about 10 in.) circumferential welds are often difficult to make unless the workpiece is rotated during welding. The difficulty is generally greater when gas metal-arc welding than when shielded metal-arc welding, because the electrode holder for gas metal-arc welding is less maneuverable than the simple electrode holder used in the shielded metal-arc process and the travel speed is greater than in shielded metal-arc welding.

The difficulty encountered in the welding of small circular parts can be minimized by the use of a suitable adapting fixture and a motorized rotary positioner. One such fixture, in which the workpieces are held securely to an adapter plate by means of an arbor and a C-washer, is shown in Fig. 12. The adapter plate is secured to a welding jig. The clamping arrangement permits quick assembly and release. The fixture is fastened to the worktable of a rotary positioner of the type shown in Fig. 16 in the article on Shielded Metal-Arc Welding, and is rotated at a speed that will provide the required rate of welding.

The circumferential welding of circular metal parts can often be facilitated by selecting the most suitable type of joint (see Example 81).

Other arrangements for holding and positioning joint assemblies are discussed in the section on Automatic Welding in this article.

Minimizing Distortion. In gas metal-arc welding, as in any other process that involves rapid local heating and cooling, distortion of workpieces is likely to occur. Sometimes distortion can be prevented simply by changing the direction of consecutive passes (see Fig. 14 in the article on Shielded Metal-Arc Welding in this volume). In other applications, there may be no practical means of keeping distortion to an acceptable level, and postweld straightening has to be done. Straightening, however, is tedious and costly and should be avoided whenever possible.

In the example that follows, straightening was eliminated by a change in fixturing.

Example 80. Change in Fixturing Method To Eliminate Postweld Straightening (Fig. 13)

Originally, the hub-and-plate assembly shown in Fig. 13 was welded on a stationary jig. Each component was secured with a toggle clamp. The operation was performed in the following steps:

1. Assemble plate and hub on stationary-jig locating pin.
2. Clamp plate and hub with toggle clamps.
3. Weld half of the circular fillet.
4. Reposition jig-and-workpiece assembly.
5. Weld second half of fillet.
6. Unclamp and lay weldment aside.

By the above procedure, weld quality was acceptable and production rate was 75 weldments per hour. However, postweld straightening was required to correct distortion of the plate; this cost approximately $1.70 per 100 weldments.

An improved procedure (Fig. 13) made use of a fixture in which the hub and the plate, located by a jig pin, were held securely against a support ring by means of a toggle clamp (not shown in Fig. 13), and two sliding cam clamps forced the ends of the plate slightly downward (the direction opposite to that in which they had originally distorted). The entire assembly was then placed on a rotary positioner and welded as it rotated in a plane 45° from horizontal. The following results were obtained:

1. Presetting of the plate eliminated the need for straightening after welding.
2. Production rate was increased to 90 weldments per hour.
3. Weld quality was improved.

Additional welding details are given in the table that accompanies Fig. 13.

Joint Design

Gas metal-arc welding is applicable to all five basic types of joint — butt, lap, T, corner and edge — and to most modifications of these basic types.

The rules of joint design for gas metal-arc welding are not necessarily different from those for shielded metal-arc welding, but some design considerations are unique to the gas metal-arc process, mainly because of the differences in size and complexity of equipment. If these differences are not taken into consideration in locating a particular weld joint, the welder may be prevented from properly manipulating the electrode holder. Joints must not be located so as to cause an excessive gap between the nozzle of the electrode holder and the root of the joint, because such a gap reduces the effectiveness of the shielding gas and may prevent root penetration. Inadequate shielding gas is evidenced by weld discoloration, excessive weld spatter, and porosity.

Recommended proportions of grooves for gas metal-arc welding are shown in Fig. 1, 2 and 3 on pages 148 to 150 in this volume. With some exceptions, the proportions of joints for gas metal-arc welding often are the same as those for shielded metal-arc welding. For joint designs used in welding 1-in. and 1½-in. plate, the reader may refer to Examples 88 and 89 (Fig. 21), on pages 94 and 95 in this article.

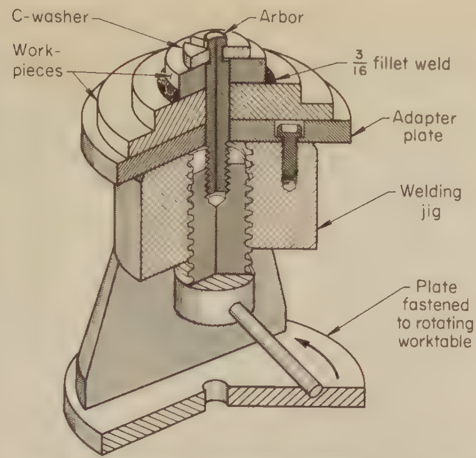
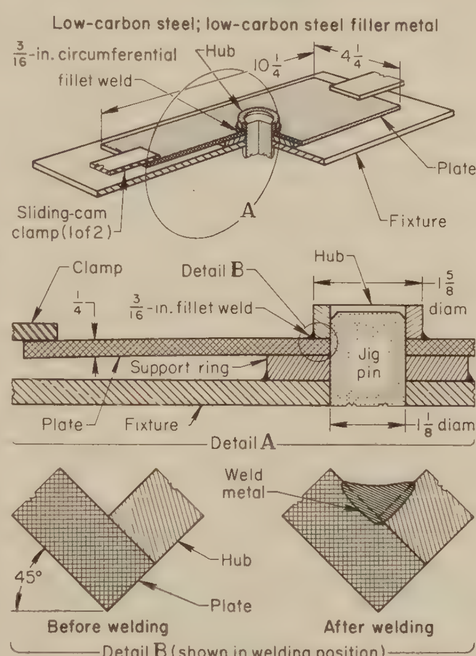


Fig. 12. Typical adapting fixture for fillet welding of small circular parts using a rotary positioner



Joint type	Circumferential corner
Weld type	$\frac{3}{16}$-in. fillet
Power supply	500-amp, constant-voltage transformer-rectifier, with slope control
Welding current	280 to 300 amp, dcrp
Electrode wire	0.045-in.-diam E70S-3
Voltage:	
Original procedure	25 v
Improved procedure	500 ipm
Shielding gas	98% argon – 2% oxygen, at 25 cfh
Wire-feed rate:	
Original procedure	440 ipm
Improved procedure	500 ipm
Production rate:	
Original procedure	75 weldments per hour
Improved procedure	90 weldments per hour

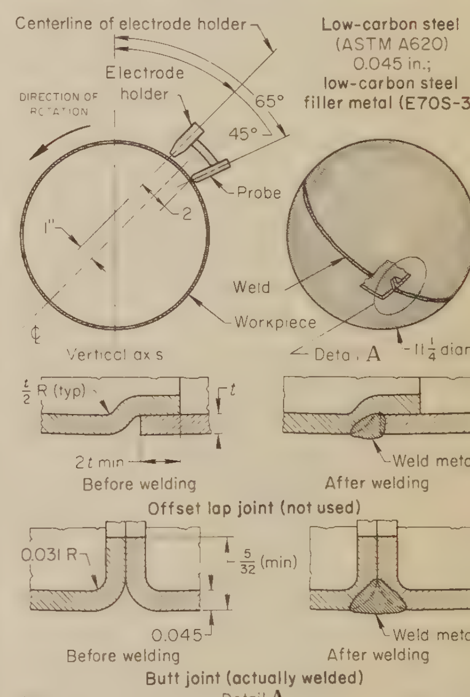
Fig. 13. Use of a special clamping fixture that eliminated a postweld straightening operation (Example 80)

Selection of Joints for Economy. Careful selection of type of joint can often result in manufacturing economies. These economies are not always confined to the welding operation, but may apply in other manufacturing operations, as shown in the next example.

Example 81. Use of a Modified Butt Joint Instead of an Offset Lap Joint To Reduce Tooling and Labor Costs (Fig. 14)

For welding the spherical refrigerant container shown in Fig. 14, an offset lap joint (middle view in Fig. 14), although frequently used in welding the components of a variety of pressure cylinders and spheres, would have resulted in high labor and tooling costs. The lip of the offset hemisphere would have caused interference in assembly, and additional tooling would have been needed to offset the lip.

The modified butt joint shown at bottom in Fig. 14 allowed use of identical forming tools for both halves of the sphere and was the best compromise among weldability, tooling costs, and labor costs. To reduce labor costs still further, each welder op-



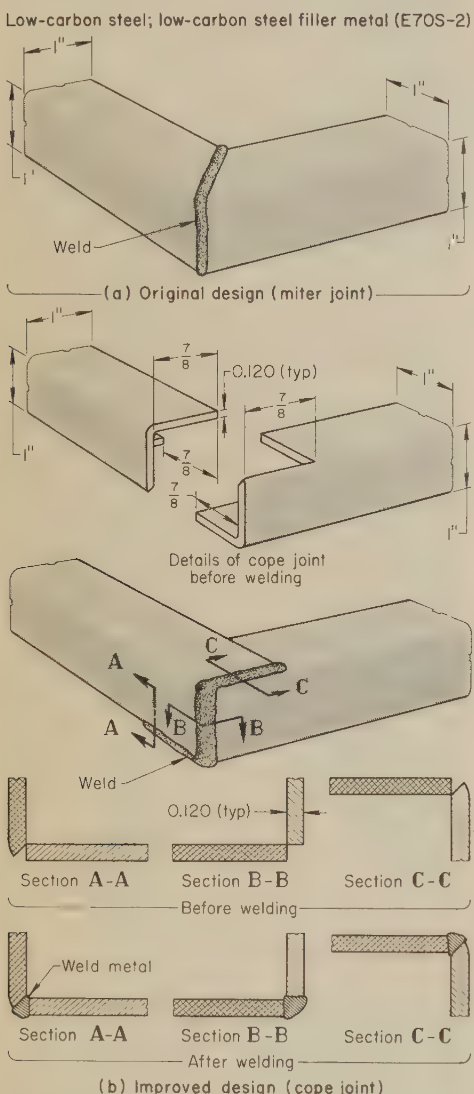
Joint type	Circumferential modified butt
Weld type	Single-flare V-groove
Power supply	300-amp transformer-rectifier
Electrode wire(a)	0.030-in.-diam E70S-3
Electrode holder	Mechanized, fixed, water cooled
Wire feed	Push-type motor, on electrode holder
Current	170 to 190 amp, dcrp
Voltage	22 to 23 v
Shielding gas(b)	98% argon – 2% oxygen, at 35 cfh
Number of passes	One
Wire-feed rate	340 to 380 ipm
Stickout	¼ to ⅜ in.
Welding speed	46.6 ipm
Weld time per container	42 sec

(a) Selection of wire wound to a large diameter eliminated need for wire straighteners and reduced leakage rate. (b) Argon of 99.999% purity from bulk-liquid holder.

Fig. 14. Girth welded refrigerant container for which labor and tooling costs were reduced by use of a modified butt joint instead of an offset lap joint (Example 81)

erated two girth welding machines, and thus was not able to observe the welding operation; therefore, automatic seam tracking was necessary.

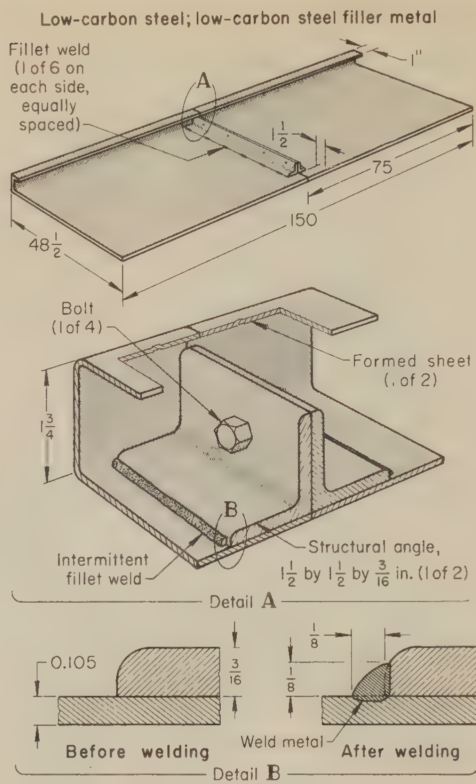
The automatic tracking system consisted of two recirculating ball-screw cross slides mounted at right angles and driven by reversible alternating-current motors. A probe, which was mounted to move with the electrode holder (see view at upper left in Fig. 14), sensed the location of the joint in relation to the electrode holder. A movement of the probe tip caused the appropriate slide to bring the probe and electrode holder back to the neutral position. The probe was mounted on a small screw-adjusted slide to provide quick and accurate adjustment of both the horizontal position of the electrode holder and the distance between the electrode holder and the work.



Joint type	Corner
Weld type	Fillet and V
Power supply	200-amp, constant-voltage rectifier
Electrode wire	0.030-in.-diam E70S-2(a)
Wire feed	Constant feed
Current	80 to 85 amp, dcsp
Voltage	26 v
Shielding gas	75% argon – 25% carbon dioxide, at 40 cfh
Wire-feed rate	30 to 100 ipm
Welding speed	10 ipm

(a) 0.04% carbon; triple deoxidized, with flash copper plating

Fig. 15. Corner section of a rectangular frame, for which a cope joint was substituted for a miter joint to improve dimensional control (Example 82)



Joint type	Lap
Weld type	2-in. intermittent fillet welds, equally spaced
Power supply	300-amp rectifier
Electrode wire	0.035-in.-diam low-carbon steel
Voltage	18 v
Shielding gas	CO_2, at 20 cfh
Welding position	Horizontal
Number of passes	One

Fig. 16. Oversize splash guard formed in two sections and joined by fillet welding and bolting (Example 83)

At the end of the welding cycle, the probe and the electrode holder were raised by the vertical slide. After the next assembly was in place, the probe and electrode holder were lowered by the same means and welding was started automatically.

The hemispheres were held in a special welding machine (lathe) consisting of one fixture rotated by a continuously variable drive and a second fixture mounted on the tailstock. Both fixtures were mounted on air-operated slides. Thus, the parts were held together and rotated under the electrode holder. When the electrode holder was retracted after completing the weld, the air cylinders separated, releasing the welded workpiece.

The operator loaded the hemispheres in the machine and pushed a button to close the fixtures. The operator then had an option of using automatic start, by which the weld started as soon as the electrode holder was in position, or manual start, whereby he could observe the position of the electrode holder, make corrections if required, and then start the weld by pushing a button. While one container was being welded, the operator loaded and started a second machine. After each container had been welded, the operator checked it for visible defects. Those requiring repair welding were set aside, and those with no visible defects were transferred on a conveyor to the testing area.

The workpiece was a disposable refrigerant container with a water capacity of 25.5 lb, produced under a special permit that specified two types of pressure tests. Each welded container was tested by subjecting it to 300-psi internal air pressure while within a heavy steel safety chamber. The pressure in the container was then reduced to 100 psi, the chamber was opened, and the sphere was forced under water to check for leaks. If repairs were required, the spheres were retested after repair. A destructive test was required on one container out of each lot of 1000, with a minimum of one per day (although in practice, at least one container was tested from each machine during each shift). This test consisted of filling the container with water, connecting it to a high-pressure pump and increasing the pressure until the container burst. The minimum bursting strength was 800 psi. Fewer than 5% of the spheres required weld repairs.

The guidance system caused some problems, primarily because of the maintenance required. Repair and adjustment of the probe switch were difficult, and improperly adjusted probes could cause misplaced welds. Spare systems were available for replacement of defective probe units.

Although the guidance system added to the machine cost and caused maintenance problems, these disadvantages were soon canceled out by decreased labor costs. Satisfactory welds were difficult to produce manually, because the horizontal variance of the electrode-holder position had to be held to 1/32 in. to prevent melt-through. In addition, it would have been necessary for the manual operator to correct for differences in the heights of the weld seams, which would have limited him to operating one machine, thus doubling the labor cost.

The hemispheres were press formed and vapor degreased. No edge preparation or postweld finishing were done. Welding conditions are given in the table with Fig. 14.

Selection of Joints for Dimensional Control. A change in design of a joint can often aid in the maintenance of close dimensional control, as demonstrated by the application described in the following example.

Example 82. Use of a Cope Joint Instead of a Miter Joint for Closer Dimensional Control (Fig. 15)

The corner-welded channel sections shown in Fig. 15 were parts of rectangular frames for data-processing machines. Originally, 45° miter joints were used (Fig. 15a), but dimensions after welding were unsatisfactory because of joint location and weld restraint.

To provide a more positive joint location with less weld restraint, cope joints (Fig. 15b) were substituted for the miter joints. Tolerances of ±0.010 in. on length and width, and ±0.032 in. on squareness were met on channel sections welded with the improved joint design.

The channel sections were contour roll formed from 0.120-in.-thick low-carbon steel strip. Pieces were cut to length by a cutoff die in a press. The cut lengths were also coped by a die in a press, and all parts were inspected. Tolerances on individual pieces were held to ±0.005 in.

Joints for Special Applications. When the length of a part to be formed from sheet metal exceeds the length of the forming dies, it may be necessary to make the part in shorter lengths and to join the parts after forming. Welding is the joining method most commonly used for these formed assemblies, but the use of welding alone can cause difficulties in some applications. In the example that follows, a problem in joining was solved with an improved joint design that incorporated both bolting and welding.

Example 83. Use of a Combination of Bolting and Welding To Minimize Warpage (Fig. 16)

The splash guard shown in Fig. 16 had to be formed in two pieces because it was too long to form from a single sheet in available equipment. Originally, the two pieces were joined by butt welding, but

this resulted in warpage. Also, grinding to remove excess weld metal left scratches on the sheet metal, and these scratches became even more noticeable after painting.

An improved method of joining eliminated warpage and the need for grinding of welds, and reduced welding time and material used. In this method the two formed sheets were butted, and two pieces of structural angle that had been predrilled in pairs and bolted together were placed on the sheets so that the angle and sheet seams were aligned. The edges of the legs of the angles in contact with the sheets were joined to the sheets by intermittent fillet welds, as shown in Fig. 16. An added advantage of this improved method was that the final joint was mechanical, which allowed the splash guard to be shipped in two pieces.

Manipulation of the Electrode Holder

For best results in flat-position welding, the electrode holder should be held nearly vertical. The angle is not critical and may be as much as 30° from vertical in any direction without any noticeable effect on results; however, if the electrode holder is positioned far from vertical, the effectiveness of gas shielding may be impaired.

The distance from the end of the contact tube to the end of the nozzle (see electrode holders in Fig. 5, page 82) should be ¼ to ⅜ in., although when using the short-circuiting mode of metal transfer, the contact tube can be extended beyond the end of the nozzle as much as ⅛ in. The amount of electrode extension from the contact tube to the weld puddle (stickout) is not critical, although it is related to the mode of metal transfer and does affect deposition rate. As stickout is increased, deposition rate increases, penetration decreases, and the amount of weld spatter increases. Also, as the stickout is increased so is the distance between the end of the nozzle and the weld puddle, and the effect of the gas shield is decreased. Generally, the end of the nozzle should be ⅝ to ¾ in. from the work (stickout of ¼ to ½ in.).

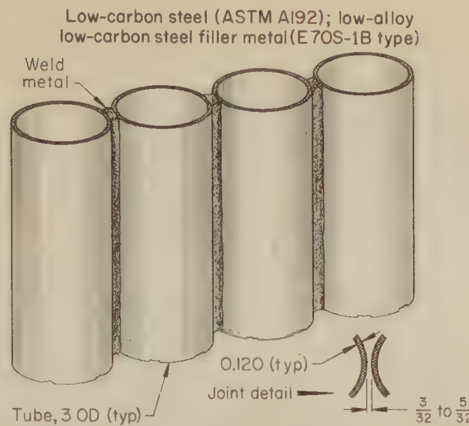
Specific types of beads can be produced by different techniques. Stringer beads generally have deeper penetration, and beads made by weaving have less penetration. In many applications of multiple-pass welding, the first pass is a stringer, and the following one or more passes are made with the weaving technique.

Direction. Both forehand and backhand techniques are used, the choice in any application depending on which technique seems to be most appropriate. The backhand technique allows the welder a better view of the weld puddle. Penetration is influenced by technique. It is greater with forehand technique than with backhand technique.

Thin Sections

The minimum metal thickness appropriate to gas metal-arc welding is about 0.020 in., which is thin enough to present problems. The most common approach to welding of thin sections (⅛ in. thick or less) is to use a short-circuiting arc, which permits metal transfer with a lower heat input than that of a spray-type arc. By this technique, adequate penetration is obtained and the possibility of melt-through is minimized. Similar results can be obtained in welding of thin sections by use of an emissive-type electrode, such as E70U-1, and straight-polarity direct current.

Examples 84, 85 and 86, which follow, describe techniques used in welding metal less than ⅛ in. thick. In Examples 84 and 85, a short-circuiting arc was used. An emissive electrode was used in Example 86. Table 6 lists other examples in this article that deal with gas metal-arc welding of thin steel.



Power supply	300-amp, constant-voltage motor-generator
Electrode wire	0.045-in.-diam low-alloy low-carbon steel(a)
Arc type	Short circuiting
Shielding gas	Carbon dioxide
Deposition rate at 100% arc time	4.1 lb/hr

(a) 0.12 C, 1.90 Mn, 0.80 Si, 0.50 Mo, and 0.10 Ni (comparable to E70S-1B)

Fig. 17. Section of a package boiler assembly that was made by welding between adjacent tubes, using a short-circuiting arc (Example 84)

Table 6. Examples in This Article That Deal With Gas Metal-Arc Welding of Metal ⅛ In. Thick or Less

Work-metal thickness, in. (a)	Example number	Work-metal thickness, in. (a)	Example number
0.035	106	0.062	86, 123, 126
0.036	108, 122		
0.042	125	0.070	102
0.045	81	0.105	83, 115, 116
0.048	98		
0.057	121	0.112	113
0.059	104	0.120	82, 84, 85
0.060	90	0.125	95, 99, 103, 107

(a) Minimum, in applications where metals of two or more thicknesses were welded.

Example 84. Use of a Short-Circuiting Arc for Welding Between 0.120-In.-Wall Tubes (Fig. 17)

A package boiler assembly was produced by welding between adjacent low-carbon steel tubes, in the vertical position. As Fig. 17 shows, the tubes were 3 in. in outside diameter and 0.120 in. in wall thickness, and were spaced 3/32 to 5/32 in. apart.

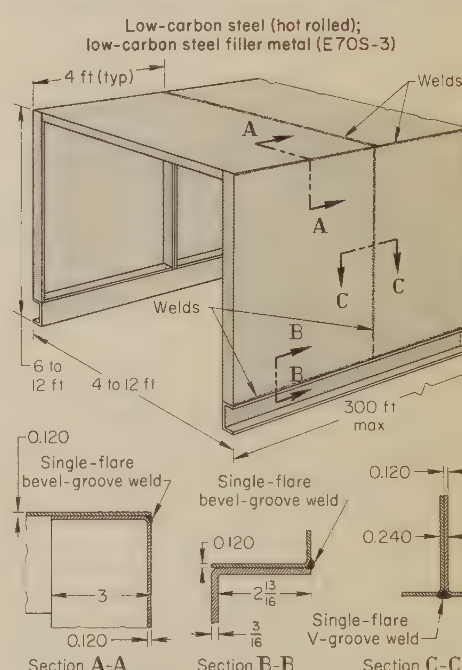
Because of the low penetration, the low heat input into the base metal, and the relatively high deposition rates that could be obtained, a short-circuiting arc was selected. The welding technique consisted in beginning the weld at the top of the tube panel and progressing downward, while oscillating the electrode holder transversely in an arc approximately 3/16 in. wide. This technique resulted in an effective seal weld. Additional welding details are given in the table that accompanies Fig. 17.

Example 85. Change From Shielded Metal-Arc to Gas Metal-Arc Welding With a Short-Circuiting Arc To Simplify Welder Training and Increase Welding Speed (Fig. 18)

Housings for spray-type, conveyorized metal-treatment equipment were made from hot rolled low-carbon steel sheet 0.120 in. thick and ranged in length from 30 to 300 ft. The height and width were 6 to 12 ft and 4 to 12 ft, respectively. Components for housings were made in 4-ft-long sections, partly fabricated in the shop, and shipped "knocked down" for field erection. Installations often involved several hundred feet of welded joints.

Conventionally, welding was done by the shielded metal-arc process, using small-diameter covered electrodes at low amperage. The training of men to use this process on 0.120-in.-thick sheet proved difficult and expensive. By changing to gas metal-arc welding with a short-circuiting arc, welder training was greatly simplified and welding speed was more than doubled.

A typical housing, together with details of the welded joints, is shown in Fig. 18. To prevent melt-through, the joints were designed for single-pass welding, and heat input was kept low by using the short-circuiting type of metal transfer. Conditions that made this type of weld deposition possible are given in the table with Fig. 18, and consisted principally of: (*a*) a constant-voltage power supply with variable inductance; (*b*) small-diameter electrode wire; (*c*) low welding current; and (*d*) a shielding-gas mixture that gave good arc stability and minimized weld spatter.



Conditions for Gas Metal-Arc Welding

Power supply	200-amp, constant-voltage rectifier, with variable inductance
Wire feed	Push type
Electrode wire	0.030-in.-diam E70S-3
Electrode holder	200 amp, air cooled
Current	140 amp, dcrp
Voltage	20 v
Arc type	Short circuiting
Shielding gas	75% argon – 25% carbon dioxide, at 15 cfh
Welding positions	Horizontal, vertical
Number of passes	One
Wire-feed rate	200 ipm
Stickout	½ to ¾ in.

Fig. 18. Field-erected housing for which changing from shielded metal-arc welding to gas metal-arc welding simplified training of welders and more than doubled the welding speed (Example 85)

Because of variations in groove size and because of the fit-up conditions that existed in field assembly, specific welding rates were not determined. However, a comparison of over-all job times showed that deposition rate in gas metal-arc welding was 2½ times the rate obtained in shielded metal-arc welding. Furthermore, slag cleaning was eliminated and weld spatter was considerably reduced.

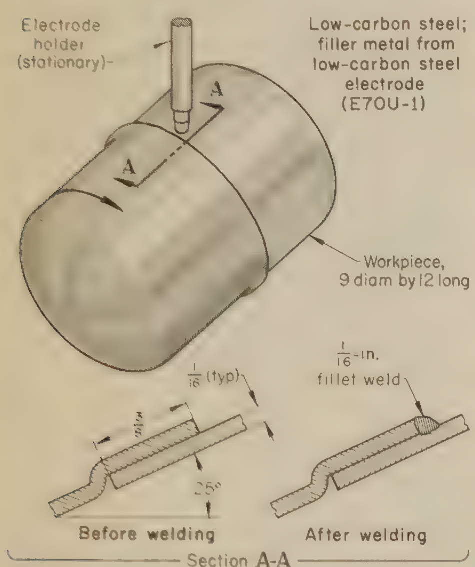
As a result of these improvements in the field, the manufacturer adopted the gas metal-arc process for welding of sheet metal in the shop.

Example 86. Use of Automatic Gas Metal-Arc Welding With Emissive Electrodes for High Welding Speed (Fig. 19)

Refrigerator compressor housings were made of two deep drawn 1⁄16-in.-thick low-carbon steel cups joined with a single-pass circumferential weld (see Fig. 19). To avoid melt-through and to obtain the high production rate demanded for the unit, the compressor housings were automatic gas metal-arc welded with emissive electrodes. Welding conditions are given in the table that accompanies Fig. 19.

The emissive coating on the electrode wire provided the arc stabilization needed to operate on straight-polarity direct current (in contrast to the reverse polarity normally used for gas metal-arc welding). The use of straight polarity provided maximum melting rate with controlled penetration. Penetration was adequate for the weld to withstand an underwater pressure test (using air at 350 psi), but did not cause melt-through.

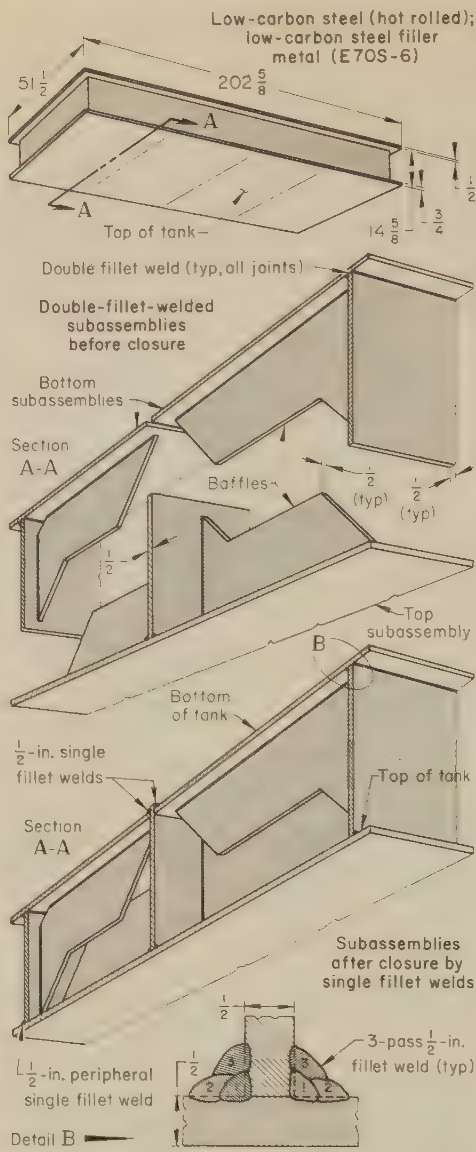
The mechanical equipment used consisted of (*a*) a clamping jig to hold the two parts in alignment at the proper angle for weld-



Joint type	Lap
Weld type	Fillet
Power supply	500-amp, constant-voltage rectifier, with wire-feed unit and cycle sequencer
Electrode wire	1⁄16-in.-diam E70U-1(a)
Electrode holder	800 amp, water cooled
Fixtures	Rotating jig, electrode-holder mount
Current	380 amp, dcsp
Voltage	26 v
Shielding gas	98% argon – 2% oxygen, at 30 cfh
Welding position	Flat
Number of passes	One
Wire-feed rate	234 ipm
Welding speed	60 ipm
Production rate	75 housings per hour(b)

(a) Emissive-coated electrode for use with straight-polarity direct current. (b) Using two welding stations.

Fig. 19. Welding position and details of lap joint for automatic welding of a compressor housing with the use of an emissive electrode (Example 86)



Joint type	T
Weld type	Fillet
Power supply	300-amp, constant-voltage motor-generator
Electrode wire	0.045-in.-diam E70S-6
Electrode holder	300 amp, air cooled
Current	200 amp, dcrp
Voltage	24 v
Shielding gas	75% argon – 25% carbon dioxide, at 15 cfh
Welding position	Flat
Wire-feed rate	300 ipm
Travel speed	16 ipm, per single bead
Welding speed	6 ipm, per full weld

Fig. 20. Heavy-duty tank for processing liquids, made up of components ½ and ¾ in. thick, fillet welded as shown (Example 87)

ing in the flat position, (*b*) a variable-speed drive to rotate the jigged part, (*c*) an adjustable mount to hold the water-cooled electrode holder in a proper fixed position, and (*d*) a wire-feed unit to supply the filler metal.

One welding operator manned two welding stations; while one station was in operation, the other was being loaded. Loading and unloading were the only manual operations. About 75 housings per hour were welded by this procedure. Arc time for each weld was only 30 sec.

After being welded, the compressor housings were pressure tested by filling them with air at 350 psi and immersing them in water on a conveyor line. An average of 3% of the welded housings were rejected for leaks in the test; about two-thirds of the rejected housings were salvaged by weld repair.

Welding cost per unit (including the cost of direct labor, filler metal and shielding gas) was 13¢. Cost of power supply, control unit, wire feed, electrode holder, cables and hoses was approximately $9000.

Intermediate and Thick Sections

In a majority of applications, the most significant difference in technique for gas metal-arc welding of intermediate and thick sections (as opposed to thin sections) is the type of arc used. For welding thin sections (⅛ in. or less), a short-circuiting arc is generally used, to minimize heat input (see Examples 84 and 85). Sections of intermediate thickness (about ⅛ to ½ in.) and thick sections (more than about ½ in.) require greater heat input, and therefore are more often welded with the use of a spray-type arc.

For groove welds, the joint design requires additional consideration as section thickness increases (see pages 148 to 150). The three examples that follow describe typical practice for welding sections ½ to 1½ in. thick.

Example 87. Fillet Welding of ½-In.-Thick and ¾-In.-Thick Components of a Heavy-Duty Tank for Processing Liquids (Fig. 20)

A large rectangular tank with baffled internal compartments was made by joining hot rolled low-carbon steel plates by fillet welds, as shown in Fig. 20. This tank was used for processing liquids, and therefore had to be leakproof. In addition, it was required to support heavy machinery mounted on its top side, and to withstand vibrational stress during operation.

To meet requirements, while maintaining a simple fabricating procedure, the tank was constructed of ¾-in. plate (top) and ½-in. plate (sides, bottom, baffles and central partition) joined by ½-in. fillet welds. Double fillet welding was used on all joints except those formed by final closure, which could only be single fillet welded from the outside.

The tank was made up of three subassemblies, as shown in Fig. 20. After fit-up, each subassembly was tack welded by the shielded metal-arc process, using 3⁄16-in. E6012 electrodes, and 200-amp alternating current from a 400-amp power supply.

The tack welded components of the subassemblies then were double fillet welded by the gas metal-arc process, under the conditions given in the table with Fig. 20. Welding was done in the flat position. No clamps were used.

For joining of the welded subassemblies to complete the tank, the top one was turned over and the two bottom ones were fitted onto it. After tack welding (same conditions as for the subassembly components), the unit was closed by means of single fillet welds (section A-A, Fig. 20).

Examples 88 and 89. Joint Design and Welding Practice for Butt Welds in Plates 1 In. and 1½ In. Thick (Fig. 21)

Example 88 — Plates 1 In. Thick (Fig. 21a). The gas metal-arc process and the single-V-groove joint design shown in Fig. 21(a) were selected for butt welding of 1-in.-thick low-carbon steel plates. This joint required 100% penetration and high quality. The gas shield permitted the welder to see the arc action without obstruction, which was helpful in obtaining the required quality.

The weld was made in nine passes, using a backing strip, as shown in Fig. 21(a). A short cooling period followed passes 3, 5 and 7. The filler metal was 1⁄16-in.-diam low-carbon steel wire fed at 220 in. per minute. Reverse-polarity direct current was

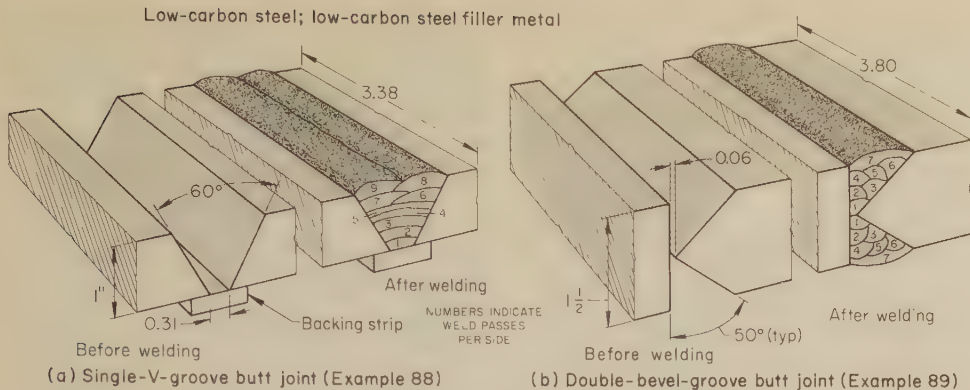


Fig. 21. Joint designs and buildup sequences for butt welding of plates 1 and 1½ in. thick (Examples 88 and 89)

used at 29 volts. A mixture of argon (at 27 cu ft per hour) and carbon dioxide (at 18 cu ft per hour) was used as the shielding gas.

Example 89 — Plates 1½ In. Thick (Fig. 21b). A double-bevel groove was selected for the butt joint in welding the 1½-in.-thick plates shown in Fig. 21(b). This type of joint was selected not only to minimize the amount of weld metal used, but also to permit full accessibility of the electrode holder and shielding gas to the root of the joint. The gas metal-arc process was selected mainly to avoid the risk of entrapping slag, which could have occurred with the shielded metal-arc process.

The weld was completed in 14 passes (seven on each side) using 1/16-in.-diam low-carbon steel electrode wire fed at 210 in. per minute. Reverse-polarity direct current was used at 29 volts. A mixture of argon and carbon dioxide was used as the shielding gas; argon flow was 27 cu ft per hour; carbon dioxide, 18 cu ft per hour.

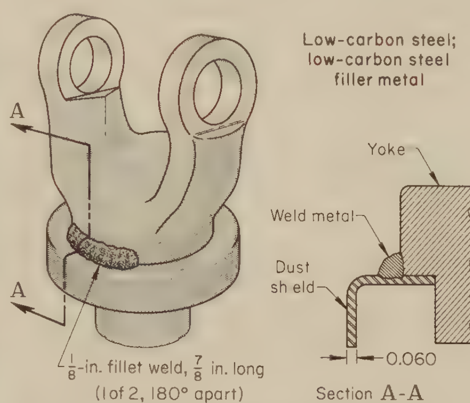
Sections of Unequal Thickness

The difference in thickness that can be tolerated between sections being welded is generally the same for gas metal-arc welding as for other arc welding processes. Often the amount of penetration required in the thicker section is the governing factor, because the current used and the resulting heat input must be low enough to avoid overheating the thinner section.

There are two possible approaches to minimizing heat-sink differential when there are wide differences in thickness between two sections. One approach is to machine a groove in the thick section close to the joint to be welded; then, in effect, two sections of more nearly the same thickness are welded. This approach is commonly used in making boilers and heat exchangers, where relatively thin-wall tubes must be welded to thick tube sheets. (For details of such a procedure see Fig. 30 in the article on Shielded Metal-Arc Welding, page 18.)

Another approach is to hold a copper backing bar or block against the thin section during welding, using the bar or block as a heat sink. (For more details on this technique, see Fig. 31 in the article on Shielded Metal-Arc Welding, page 19.)

In many applications, if requirements are not stringent, a considerable difference in thickness between parts being welded can be tolerated without the use of special techniques. One such application is described in the example that follows.



Electrode wire	0.035-in.-diam low-carbon steel(a)
Current	160 amp
Voltage	23.5 v(b)
Shielding gas	Carbon dioxide, at 20 cfh
Wire-feed rate	276 ipm
Stickout	7/16 to ½ in.
Welding speed	17.5 ipm
Welding time per piece (two welds)	6 sec

(a) 0.17 C, 1.44 Mn, 0.017 P, 0.023 S, 0.56 Si. (b) Direct meter reading across arc.

Fig. 22. Universal-joint assembly in which a dust shield of formed thin sheet was welded to a heavy-section forging (Example 90)

Example 90. Welding 0.060-In. Sheet to a Thick Section (Fig. 22)

A dust shield made from 0.060-in.-thick low-carbon steel was welded to a relatively thick yoke forged from low-carbon steel, to make the universal-joint assembly shown in Fig. 22.

The dust shield was supported on a cutout ring, and clamping pressure was applied on the end of the yoke to hold the parts in position for welding. Welding was done by the gas metal-arc process, using a hand-manipulated water-cooled electrode holder at a 45° work angle and a 0° lead angle. The electrode wire was fed by a motorized wire feed. Additional welding details are given in the table that accompanies Fig. 22. Thousands of these assemblies were produced, with no melt-through of the 0.060-in.-thick sheet.

Weld Design for Improved Accessibility

The complexity of the electrode holders used in gas metal-arc welding may make the process less versatile than the shielded metal-arc process for applications in which welding is done on intricate assemblies that have joints in difficult-to-reach locations.

Suitable fixtures and positioning devices can greatly increase the versatility of gas metal-arc welding (see the section in this article on Holding and Handling Workpieces, page 90, and the section on Jigs, Fixtures and Positioners on page 11 in the article on Shielded Metal-Arc Welding).

Sometimes the gas metal-arc process can be simplified, or its efficiency can be increased, by minor changes in weld design — particularly in placement of the welds for greater accessibility. Two weldments that serve as examples are shown in Fig. 23 and 24.

Figure 23 shows a three-piece weldment that requires a square-groove butt weld at one end, and a fillet weld for securing a section of tubing in place at the other. If the fillet weld were to be made as an ⅛-in. continuous circumferential bead (Fig. 23a), this would present two difficulties: (*a*) the two welds could not be made in one setup, because the wire-feed rate required for

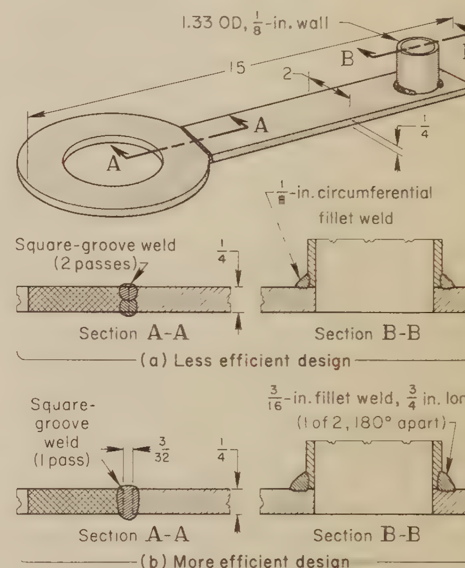


Fig. 23. Three-piece weldment for which change in size and placement of fillet weld would allow use of same wire-feed rate for both welds, and would improve joint accessibility

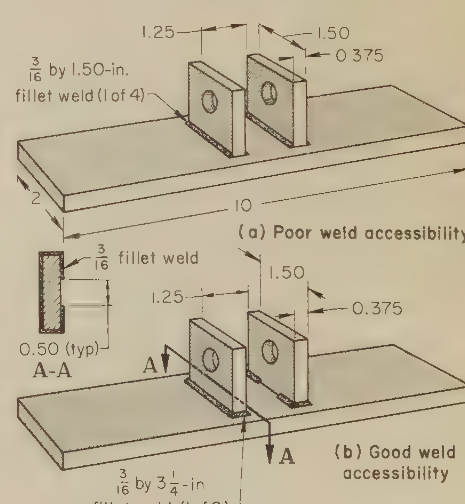
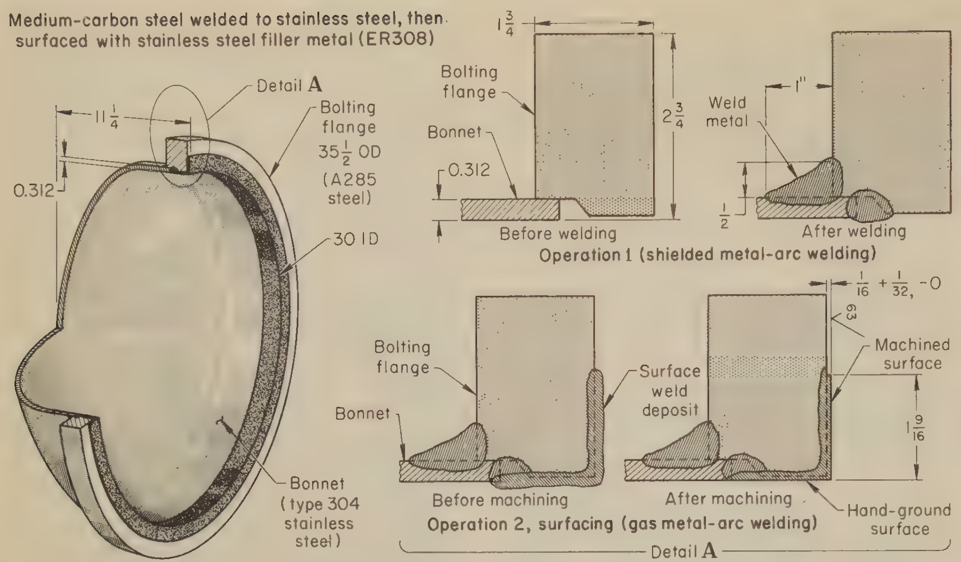


Fig. 24. Assembly for which relocation of fillet welds would improve accessibility and thus allow use of gas metal-arc welding



Conditions for Gas Metal-Arc Welding

Surface preparation	Sand blasting	Welding position	Flat
Power supply	300-amp transformer-rectifier	Number of passes	Two or three
Electrode wire	0.035-in.-diam ER308	Welding speed	37 ipm
Electrode holder	Fixed; rated at 250 amp	Gas metering	Flowmeter
Current	165 amp, dc	Stickout	½ in.
Voltage	31.5 v	Preheat (start)	200 F
Shielding gas	95% argon – 5% oxygen, at 30 cfh	Interpass temperature	200 to 300 F
		Postheat	None

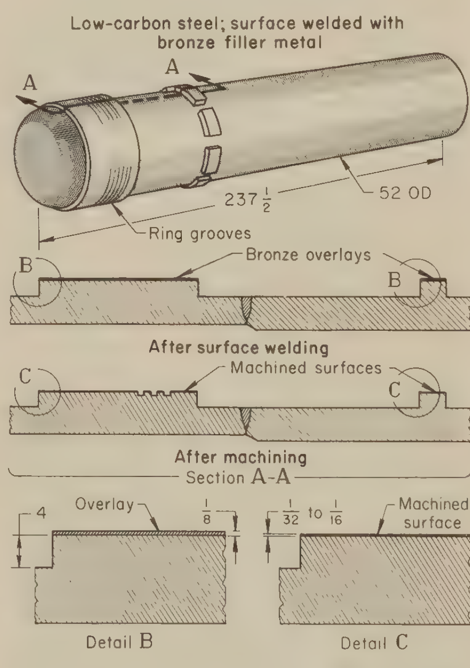
Fig. 25. Water bonnet for which cost of material was reduced by use of a carbon steel bolting flange with a surface deposit of stainless steel (applied by gas metal-arc welding, under conditions listed in the table), instead of a solid stainless steel flange (Example 91)

the butt weld would not be appropriate for the fillet weld; and (*b*) welding completely around a small circumference would be difficult unless the workpiece were rotated. If the weldment were to be redesigned so that a larger (3⁄16-in.), two-segment fillet weld (Fig. 23b) replaced the complete circumferential fillet weld, the same wire-feed rate could be used for both the butt and the fillet welds. The change from a circumferential to a two-segment weld would also greatly increase accessibility. Also note in Fig. 23 that the square-groove butt weld would require two ⅛-in. welds (one on each side) and that there would be no root opening. In the more efficient design (Fig. 23b), a 3⁄32-in. root opening could be used, which would permit the weld to be made with a single-pass ¼-in. weld (one side only).

Figure 24(a) shows a weldment designed with four fillet welds. With the fillet placement shown, gas metal-arc welding would be impractical, because the 1.25-in. space between the two components would not permit access by the electrode holder for the full 1.50-in. weld length. Changing weld placement as shown in Fig. 24(b) would provide essentially the same fillet length, and reduce need for accessibility so that gas metal-arc welding could be used.

Surfacing Applications

Gas metal-arc welding can be adapted to various applications of surfacing — an operation in which metal is welded onto the surface of another metal to confer corrosion resistance or some other specific property, or to salvage a part (see also the article on Hard Facing by Arc Welding, beginning on page 152 in this volume).



Weld type	Surfacing
Power supply	500-amp, pulsed-arc welder
Electrode wire	1⁄16-in.-diam ECuAl-type wire
Electrode holder	Air cooled, manually held
Wire feed	Push-pull, speed-control dial
Fixture	50-ton variable-speed rolls
Current, average	250 to 280 amp, dcrp
Voltage:	
Background	27 v
Pulse peak	47 v
Shielding gas	Argon, at 20 to 25 cfh
Welding position	Horizontal rolled
Number of layers	One
Stickout	½ in.
Welding speed	10 ipm
Bead height	⅛ in.

Fig. 26. Cast steel hydraulic-jack piston, and details of the bronze overlays deposited by pulsed-arc gas metal-arc welding (Example 92)

Some surfacing operations are automated in order to obtain uniform deposits. The four examples that follow describe techniques used for typical surfacing applications.

Example 91. Cost Reduction by Use of a Stainless Steel Surfaced Carbon Steel Flange Instead of a Solid Stainless Steel Flange (Fig. 25)

Figure 25 shows a water bonnet for a water cooler (shell-and-tube process) that was required to have a corrosion-proof tube chamber. This requirement was met by shielded metal-arc welding a sand blasted carbon steel bolting flange to the stainless steel bonnet (Operation 1 in Fig. 25), and then gas metal-arc welding a surfacing deposit of stainless steel to the inside of the flange and to the gasket face of the flange (Operation 2 in Fig. 25). The original design of this weldment had specified a solid stainless steel bolting flange, but because of the quantity required, and the size and shape of the flange, procuring it in solid stainless steel proved to be difficult and costly. The use of the low-carbon steel flange surfaced with stainless steel resulted in a 50 to 60% saving in cost of material.

The use of a carbon steel bolting flange clad with type 304 stainless steel had been considered, but it was difficult and expensive to procure clad material in the required thickness and in small quantities (some mills would supply only a complete mill run). Sprayed-on stainless steel was tried, but was discarded because of the porosity of the deposits.

For the surfacing operation, the weldment was mounted on a conventional mechanical positioner and was supported on turning rolls. The starting area was preheated with a gas burner to 200 F, and the surfacing weld was deposited in the flat position. Two or three passes were required, depending on the buildup necessary. The interpass temperature was held between 200 and 300 F. (Both the preheating and the interpass temperatures were measured by temperature-indicating crayons.) No postheating was required. After welding, the surfaces were visually inspected for porosity. The bonnet conformed with Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code, and the welder was qualified under the rules of Section IX of that code.

As shown at lower right in Fig. 25, the surfacing deposit corresponding to the inside diameter of the bonnet was hand ground flush with the wall of the semi-elliptical head, and the deposit corresponding to the face of the bolting flange was machined to provide a 1⁄16-in.-thick seal and a raised face. Additional conditions for the surfacing operation are given in the table that accompanies Fig. 25.

Example 92. Gas Metal-Arc Welding With Pulsed-Arc Transfer for Depositing a Bronze Overlay on Bearing Areas of Hydraulic Jack Pistons (Fig. 26)

In the manufacture of a 48-ton hydraulic-jack piston (see Fig. 26), the surfaces of the piston in contact with the cylinder wall were coated with bronze overlays by gas metal-arc welding, using pulsed-arc transfer. This method for depositing the overlays was selected to avoid difficulties experienced with similar but smaller units having wall thicknesses of 3 to 5 in. The overlays on these smaller pistons had been applied manually by the shielded metal-arc process, and deposition was relatively slow. Another problem encountered with the smaller pistons was that scattered areas of severe porosity were evident after the rough machining cut on the overlays. These had to be machined out and rewelded, which was time-consuming and costly.

For the surfacing operation, the machined piston, which had been made by joining three low-carbon steel castings with submerged-arc girth welds, was placed on a 50-ton variable-speed roll positioner for rotation during welding. One layer of bronze

about ⅛ in. thick was deposited by the gas metal-arc process, as shown in Fig. 26. The electrode holder was manipulated manually, and a ½-in.-wide bead was deposited, with ⅛-in. overlap. No preheat or postheat was used; other conditions for the surfacing operation are given in the table that accompanies Fig. 26.

Visual inspection after a rough machining cut on each overlay showed no porosity and no lack of fusion, and no pistons surfaced by the gas metal-arc process were rejected. Time for depositing the bronze layers was about one-fourth that predicted from experience with the shielded metal-arc method. As shown in detail C in Fig. 26, the bronze overlays were 1⁄32 to 1⁄16 in. thick after final machining.

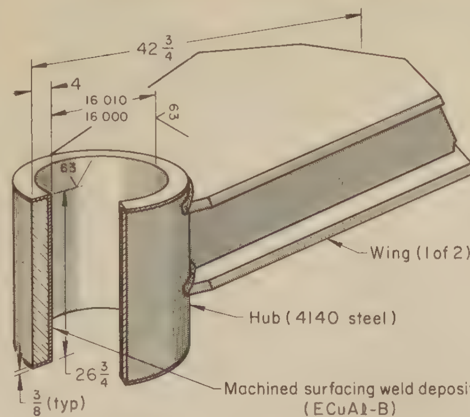
Example 93. Elimination of Preheat and Interpass Heating To Avoid Disturbance of the Gas Shield and Resultant Porosity of Welds (Fig. 27)

After the trunnion-hub assembly shown in Fig. 27 had been welded and stress relieved, a copper alloy surface weld deposit ½ in. thick, to give a ⅜-in.-thick finished dimension, was applied to the bore and ends of the hub by the gas metal-arc process. The hub was used on a floodgate, and the surfacing was required for corrosion resistance.

An insulated box, 7 ft square and 3 ft deep, was made to fit a 2000-lb-capacity welding positioner so that the hub, with the wings welded to it, could be rotated for the surfacing operation. The electrode holder was mounted on a fixture, but was operated manually, for welding inside the bore of the hub.

Preheating to 400 F and heating to hold the interpass temperature at 200 to 300 F was tried, but the draft from the burners under the insulated box disturbed the shielding-gas cover, and porous welds resulted. By eliminating preheating and interpass heating, 90% of the porosity was eliminated. It was also found that a shielding gas of 90% helium, 7½% argon, and 2½% carbon dioxide could be replaced by argon gas at about one-sixth the cost. Additional conditions for surface welding are given in the table with Fig. 27.

4140 steel; surface welded with copper alloy filler metal (ECuAl-B)



Weld type	Surfacing
Power supply	600-amp rectifier
Electrode wire	⅛-in.-diam ECuAl-B
Electrode holder	Fixture mounted, water cooled
Wire feed	Automatic
Fixtures	Rotating positioner, counterweighted electrode-holder fixture for horizontal and vertical travel
Current	280 amp, dcrp
Voltage	30 v
Shielding gas	Argon, at 35 cfh(a)
Welding position	Flat
Wire-feed rate	225 ipm
Preheat and interpass heat	None
Surface welding time per hub	48 hr

(a) Replaced mixture of 7½% argon, 90% helium, and 2½% carbon dioxide

Fig. 27. Floodgate trunnion on which the hub was surface welded without preheat or interpass heat, to reduce porosity (Example 93)

Various types of vessels used in papermaking undergo corrosive wear due to chemical action in reducing wood to pulp, bleaching and other operations. Low-carbon steel vessels often have a short life expectancy, but because of their low cost, it is sometimes more economical to replace or salvage them than to make the vessels from more costly corrosion-resistant alloys.

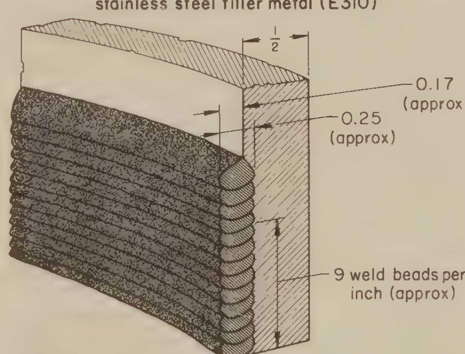
Salvaging is accomplished by surfacing the eroded walls of the vessel with a corrosion-resistant filler metal, as described in the following example.

Example 94. Surfacing a Low-Carbon Steel Paper-Pulp Digester With Stainless Steel for Corrosion Resistance (Fig. 28)

Paper-pulp digesters made of low-carbon steel, which were subject to rapid wear by corrosion, were salvaged by being gas metal-arc surface welded with E310 stainless steel filler metal when wall thicknesses reached the minimum safe limit. Although some of these vessels were surfaced by manual welding, operator fatigue and error often resulted in nonuniform and defective deposits. Automatic welding, under the conditions in the table with Fig. 28, provided more uniform deposits, with fewer defects, at lower cost and with less delay in returning the vessels to service.

The inside surface of the cylindrical wall of each vessel was welded with the vessel in a fixed vertical position and with the welding head rotated about a central shaft. Successive circumferential beads were deposited in vertical progression to the top edge of the vessel. Minimum dilution of the

Low-carbon steel; surface welded with stainless steel filler metal (E310)



Weld type	Surfacing
Electrode wire	0.062-in.-diam E310
Fixtures	Vertical rotating shaft with boom
Current	300 amp, dcrp
Voltage	27 v
Shielding gas	Argon, at 35 cfh
Welding position	Horizontal
Wire-feed rate	210 ipm
Travel speed	36 ipm
Nozzle-to-plate distance	¾ in.
Bead overlap	⅓ to ½ of previous bead
Vertical progression	9 beads per inch, approx
Weld depth	0.25 in., approx
Buildup	0.17 in., approx
Deposition rate	11 lb per hour

Fig. 28. Portion of the wall of a low-carbon steel paper-pulp digester on which overlapping beads of stainless steel were deposited by automatic gas metal-arc surface welding, under conditions in table (Example 94)

E310 stainless steel deposit with the base metal was achieved by lapping each weld bead ⅓ to ½ over the face of the preceding bead (see Fig. 28).

Welding equipment was the same as for any automatic gas metal-arc welding setup, including a power supply, a wire-feed mechanism, shielding-gas supply, and a control panel — all installed inside the vessel. The central shaft operated like a rotating manipulator, with the welding head being mounted at the end of a boom. The axis of the welding torch was radial and, in addition, was inclined at 30° to the horizontal with the tip pointing down.

Automatic Welding

Use of automatic gas metal-arc welding is considered when one or more of the following conditions prevail:

1 Quantity of similar parts to be welded is large enough to warrant the cost of using specially designed fixtures and mechanisms.
2 Skilled welders (needed for semiautomatic welding, with hand-held electrode holders) are not available.
3 Workpiece configuration or the type of welding (surfacing, for example) makes the use of a hand-held electrode holder impractical.

Tooling for automatic welding is likely to be prohibitively expensive, or to be impractical, where:

1 The required weld is such that the arc must operate successively in more than one plane.
2 Several changes of welding direction or location are required.
3 Welding conditions must be changed during the cycle.

The configuration of the workpiece, especially if it requires a more difficult-to-deposit weld bead, is a major factor to be considered in arriving at a decision as to whether or not to use automatic welding. Although automatic welding can be applied to almost any joint or series of joints, the cost of tooling may be prohibitive even if production quantities are large.

In most applications, tooling can be simplified by moving the components to be welded while the electrode holder remains stationary, but if the workpiece is large or of complex shape, moving it may not be practical, and the more costly alternative of moving the electrode holder will have to be adopted.

Circumferential welding is usually easy to automate, because round workpieces of all sizes can almost always be held and rotated without difficulty. In practice, the electrode holder remains stationary and makes the weld as the workpiece slowly rotates. Lathes are ideal for this type of operation. The workpiece is chucked between the headstock and the tailstock, and the electrode holder is mounted on the tool carriage. Depending on how the particular lathe is equipped, the operation can be automated to almost any degree. The welding current must bypass the lathe bearings, to avoid damaging them. Circular welding is also readily mechanized, using a rotating worktable.

Production Examples. The eight examples that follow describe production applications in which automatic gas metal-arc welding proved advantageous.

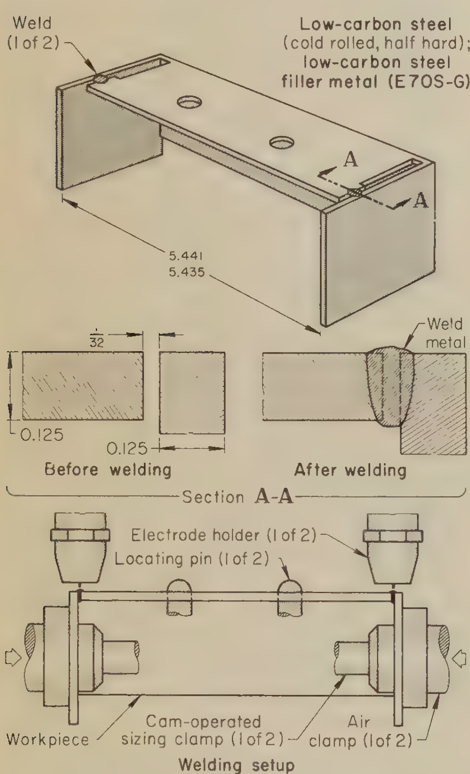
Example 95. Change From Semiautomatic to Automatic Welding That Resulted in a Saving of Time and Material (Fig. 29)

The handle assembly shown in Fig. 29 was part of a hand-operated business machine. Originally, the two welds were made by the semiautomatic gas metal-arc process (manually operated electrode holder),

using a short-circuiting arc. Later, increased production demand warranted the cost of an automatic welding system (about $6000 for welding equipment and $3000 for a fixture). The setup for the automatic system is shown schematically in Fig. 29. The short-circuiting method of gas metal-arc welding was also selected in the automatic system because of its simplicity in automating, reliability and availability.

The automatic system allowed the operator to load the workpiece on locating pins in the fixture with one hand and, with one motion of the other hand, to activate the cam-operated sizing clamps and the air clamps and to trigger the electrode holders. After welding, a built-in clamp-release delay allowed the welds to cool in the fixture, which prevented weld shrinkage and loss of dimensional accuracy. Operating conditions for automatic welding are given in the table with Fig. 29.

In comparison with the semiautomatic method, the automatic system placed the weld deposits more accurately, and thus less filler metal was needed. Also, the appearance and consistency of the welds were improved. Production rate was nearly tripled, resulting in a saving of 45 man-

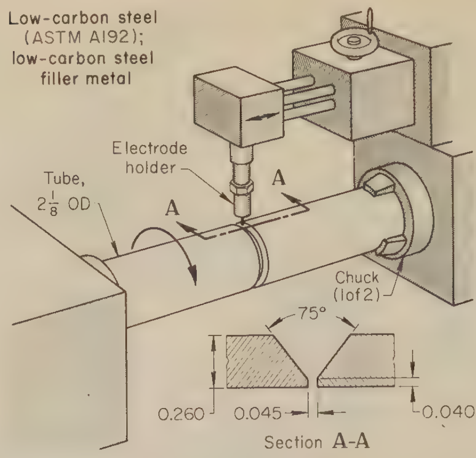


Automatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Square groove
Power supply	300-amp, three-phase, constant-voltage rectifier
Electrode wire	0.030-in.-diam E70S-G
Electrode holder	Time controlled(a)
Wire feed	Push type, with arc-spot timer and burnback control
Current	190 amp, dcrp
Voltage	30 v
Arc type	Short circuiting
Shielding gas	Argon and carbon dioxide, both at 10 cfh
Welding position	Flat
Wire-feed rate	430 ipm
Welding time	0.7 sec
Production rate	1.158 hr per 100 pieces(b)

(a) Operated in sequence with clamps. (b) Standard hours. When semiautomatic method (hand-held electrode holder) had been used, 100 pieces required 3.268 standard hours.

Fig. 29. Business-machine handle assembly that was welded by automatic gas metal-arc welding in the setup shown, to reduce labor and material costs (Example 95)



Power supply	300-amp rectifier, with variable slope and inductance
Current	Direct, reverse polarity
Electrode wire	0.030-in.-diam low-carbon steel
Shielding gas	80% carbon dioxide – 20% argon
Deposition rate	3¼ lb per hour
Welding time per tube	2 min, 21 sec

Fig. 30. Setup and design of joint used in automatic gas metal-arc welding of tubes for pressure piping systems (Example 96)

hours per week (in the production of 3000 pieces per week), and operator fatigue was considerably reduced.

Quality control consisted of destructive testing of one part out of each 1000 parts, and visual inspection for weld penetration of one part out of each 25. On more than 500,000 parts produced, virtually no field failures were reported.

Example 96. Butt Welding of Tube Sections (Fig. 30)

Sections of steel tubing of a variety of compositions (including ASTM A192) were welded together for use in pressure piping systems, using special automatic welding equipment and a special setup. As shown in Fig. 30, the tubes were held in alignment between hollow universal chucks, with the weld joint (see section A-A in Fig. 30) centered beneath the welding head. At the start of the welding cycle, the tubes were rotated synchronously as the electrode holder initiated the arc. The welding head oscillated in a plane transverse to the direction of welding, thereby distributing the weld puddle evenly between the two tubes.

Although the welding operation was fully automatic up to completion of the weld, loading and unloading of tubes were performed manually.

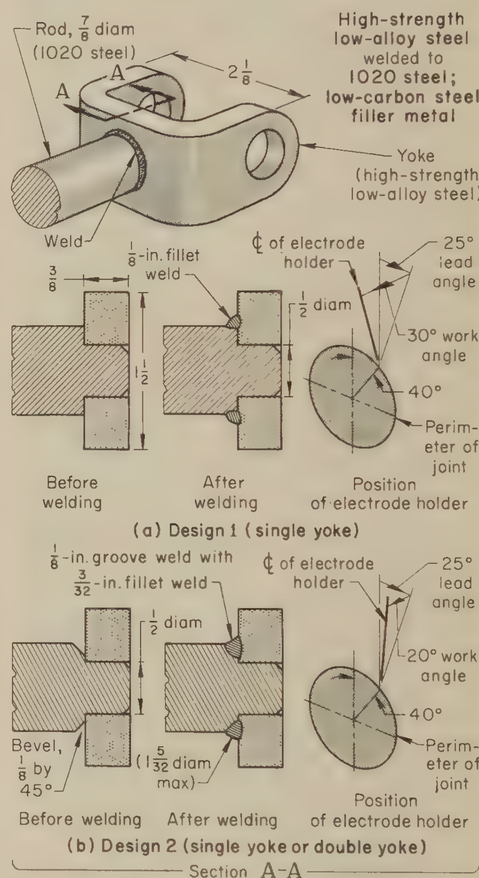
Example 97. Automatic Welding of Universal-Joint Assemblies for Uniform Strength and Dimensional Accuracy (Fig. 31)

Figure 31 shows two designs of joints used in welding 1020 steel rods to yokes made of high-strength low-alloy steel (0.22 max C, 1.25 max Mn, 0.04 max P, 0.05 max S, 0.30 max Si, 0.02 to 0.07 V, 0.20 min Cu), in the production of single-yoke and double-yoke universal-joint assemblies. These weldments were used in steering mechanisms for trucks and agricultural machines, and were required to withstand a testing torque of 4000 in.-lb. In addition, the welds made in the assemblies of bevel-joint design (Fig. 31b) had to be held to close dimensional tolerances to avoid subsequent machining in the weld area. These requirements were met by the use of automatic gas metal-arc welding, under the conditions listed in the table with Fig. 31.

On some single-yoke assemblies, the rod was not beveled at the joint with the yoke (Fig. 31a). On other assemblies, both single-yoke and double-yoke, the rod *was* beveled (Fig. 31b) — not for weld strength, but to avoid a machining operation for maintaining a maximum weld diameter of $1\frac{5}{32}$ in. This maximum diameter was required for fit of a $1\frac{5}{32}$-in.-ID washer on the rod against the yoke. Positions of the electrode holders in welding joints of both designs were the same, except that a smaller work angle was required for the beveled joint (see views at right in Fig. 31a and b).

The tooling used to align the components for welding was the same for all assemblies. The yoke was picked up by a V-type locator in the driving end of the lathe-type welding machine. For single-yoke assemblies, the yoke was held on centerline to receive the piloted end of the shaft, which was slipped into the hole in the yoke. Double-yoke assemblies were aligned in a similar manner, except that the assembly fixtures were the same at both ends.

The single-yoke assemblies were held in position for welding with a self-centering cone adapter that lined up the shaft with the centerline of the yoke. A longitudinal force of 500 lb applied at the tailstock held the assembly in alignment for welding.



Electrode wire	0.035-in.-diam low-carbon steel(a)
Electrode holder	Air cooled; side-delivery gas tube
Current	195 amp, dcrp(b)
Voltage	21 v(c)
Shielding gas	Carbon dioxide, at 50 cfh(d)
Wire-feed rate	350 ipm
Stickout	½ in.
Welding speed	18 ipm
Welding time	9 sec
Electrode wire consumed per piece	52¼ in.

(a) 0.17 C, 1.44 Mn, 0.017 P, 0.023 S, 0.56 Si. (b) From constant-voltage power supply with secondary reactance. (c) Direct meter reading across arc. (d) Flow rate was high to maintain proper shielding; with the air-cooled electrode holder and side-delivery gas tube, lower flow rates resulted in poor shielding due to drafts, and reworks were necessary.

Fig. 31. Universal-joint assembly for which automatic gas metal-arc welding was used on joints of two different designs (Example 97)

A variable-speed direct-current motor was employed to control the rotational speed of the welding lathe, and a timer controlled the duration of the welding cycle. The two welds required on assemblies with yokes at both ends of the rod were deposited simultaneously.

Example 98. Use of Automatic Gas Metal-Arc Welding for High-Quality Welds in Bell-and-Tube Assemblies (Fig. 32)

A manufacturer of universal joints and drive-line components for agricultural implements selected the automatic gas metal-arc process to weld assemblies consisting of shield bells and tubes in a variety of designs and sizes. A typical assembly after welding is shown in Fig. 32, together with sectional views of the weld-joint area of a bell joined to the tube with a continuous circumferential weld (design 1) and with four 1-in.-long intermittent welds, spaced 90° apart around the periphery (design 2). The intermittent-weld design was necessitated by the presence of equally spaced drive lugs on the outer surface of some bells.

The gas metal-arc process was chosen because of its ability to satisfy several major requirements, including high welding speed, good appearance of welds, a weld strength equivalent to the strength of adjoining parts, and the elimination of cleaning operations after welding.

The setup included a welding lathe designed to handle a variety of assemblies, a rake-off bar that prevented lateral travel and shifting of the shield bell, V-locators positioned along the tube (see view at top in Fig. 32), and a retractable headstock and tailstock fitted with bearing-surface locators. An air-hydraulic actuator connected to a rack and pinion was employed to rotate the lathe spindle 360° (for a continuous circumferential weld) or in quadratic intervals (for intermittent welding) and to control rotational speed.

Because hundreds of different combinations of tube lengths (ranging from 4 to 120 in.), bell sizes and bell shapes were welded, it was desirable to standardize the wall thickness and inside and outside throat diameters of the bell to minimize both tooling costs and setup time. In all assemblies, the inner surface of the throat of the bell served as a bearing surface for mounting the bell on the headstock during welding, while the outer surface served as a bearing surface for connecting bell and tube. Both bearing surfaces on the bell served as principal locating areas for the assembly and were vital for preventing mislocated welds.

Before being welded, tubes were cut to length in an automatic cutoff machine. Tubes and bells were assembled in one of two ways, depending on the type of weld. Tubes for circumferential welding were expanded and swaged over the outside throat diameter of the bell. Tubes for intermittent welding were also expanded and swaged to fit over the bell throat, but the two components were assembled by press fitting. After assembly, holes were punched in bells, as required. These preliminary assembly operations required more time than did the welding cycle.

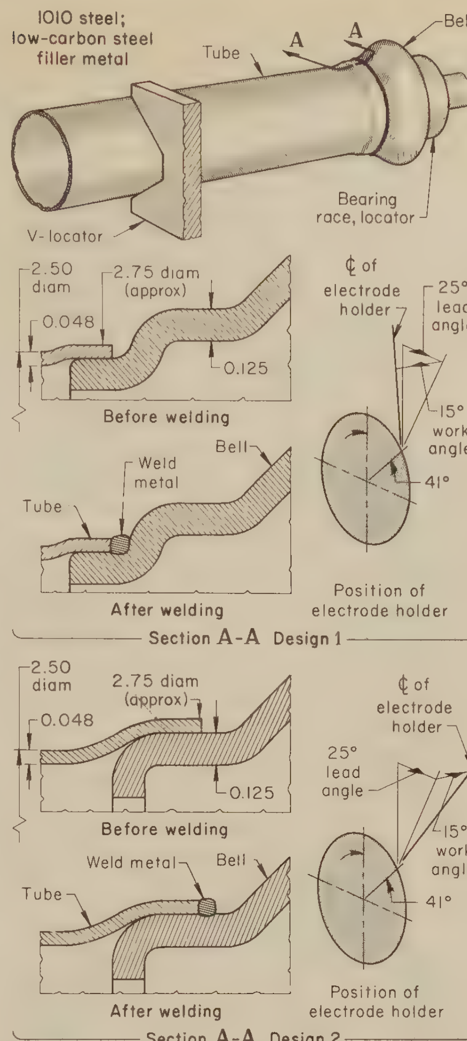
At the outset of the welding cycle, a preassembled tube and bell were placed in the lathe by setting the tube in the V-locators. By depressing a foot switch, the headstock tooling (including the internal bearing-surface locator) was extended to position in the bell. Rotation of the spindle began, and the tailstock was then brought into position at the tube end. Pressure at the headstock was 10 psi higher than that at the tailstock, to prevent the tailstock from pushing the weld joint out of alignment with the electrode holder. The electrode holder was brought into position (see Fig. 32) and peripheral welding (either continuous or intermittent) was accomplished without external backing, using self-backing joints (section A-A in Fig. 32).

Additional welding conditions are given in the table that accompanies Fig. 32. These conditions apply specifically to an assembly consisting of a 1010 steel tube, 2½-in. OD with a 0.048-in.-thick wall, and of a 1010 steel shield bell, 0.125 in. thick. The tube was expanded to an inside diameter of 2.655 to 2.660 in. and an outside diameter of about 2¾ in. This assembly, shown as design 1 in Fig. 32, required a continuous weld.

When welding was completed, the headstock retracted, and the finished assembly fell from the V-locators into a finished-part holder. The machine was then ready for the next part, with both the headstock and the tailstock retracted.

The shield-bell assembly shown as design 2 in Fig. 32 presented a special problem because of drive lugs that were spaced 90° apart on the outer surface of the bell. This press-fitted assembly required the use of the rack and pinion on the welding lathe to ensure that the spindle would always return to a common starting point and that the electrode holder would skip past the drive lugs to produce an intermittent weld. Although the basic welding conditions did not differ markedly from those for the continuous circumferential weld, welding (or arc) starts were inconsistent, resulting in inconsistent weld lengths. This condition was encountered using reactance in the circuit and maximum amperage on the 0.035-in.-diam electrode wire. The problem was solved by adding a contactor that bypassed the reactor at the start of the weld. Thus, at the instant the arc was established, the contactor dropped out, providing reactance in the circuit, but when the electrode touched the work, reactance was eliminated and power was supplied at straight constant voltage. This resulted in good starts and welds of consistent length.

The presence of a light film of oil in the weld zone, due to cutoff coolant or swaging and expanding lubricants, was not deleterious. The violent agitation of the welding arc, characteristic of the gas metal-arc process, helped in volatilizing such contaminants, thereby minimizing the possibility of blowholes or porosity.



Welding Conditions for Design 1(a)

Electrode wire	0.035-in.-diam low-carbon steel(b)
Current	220 amp, dcrp
Voltage (across arc)	22 v
Shielding gas	Carbon dioxide, at 50 cfh
Stickout	½ in.
Wire-feed rate	400 ipm
Wire consumed per weldment	59¾ in.
Welding speed	58.5 ipm

(a) Design 1 had a continuous circumferential weld. Design 2 (four 1-in.-long intermittent welds, 90° apart) was welded under similar conditions except as noted in the text of Example 98. (b) 0.17 C, 1.44 Mn, 0.017 P, 0.023 Si.

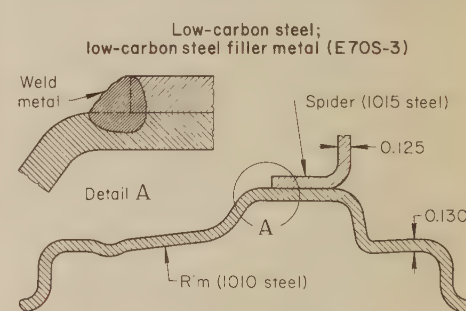
Fig. 32. Two designs of joints between shield bells and tubes that were automatically gas metal-arc welded, using V-locators and electrode-holder positions as shown (Example 98)

Example 99. Use of Automatic Gas Metal-Arc Welding for Joining Rim and Spider of Automotive Wheels (Fig. 33)

Figure 33 shows a cross-sectional view of an automotive wheel comprised of a 1010 steel rim and a 1015 steel spider. The rim was a ring of strip steel, butt welded, and roll formed to shape. The spider was a stamping with four legs that were press fitted into the rim.

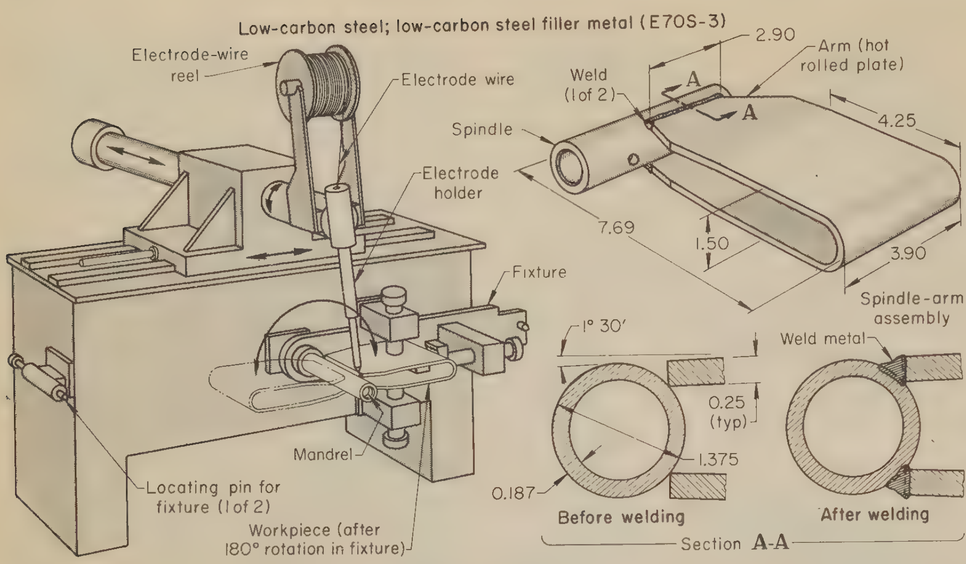
Because of the varied cyclic loading exerted on the wheel during service, it was necessary to select the welding process and weld location that would provide maximum resistance to fatigue failure. The design of the wheel assembly dictated the use of gas metal-arc welding instead of resistance spot welding (the usual process).

The wheel was welded on a high-speed production line that consisted of a die pressing station for assembly and staking, an automatic welding station with four automatic arc welding heads (one for each leg of the spider), and a valve-piercing station. The positioning of the spider leg was held to a tolerance of ±0.015 in., to



Joint type	Lap
Weld type	Continuous fillet
Length of weld	4 in., curved
Power supply	500-amp, 40-v, constant-voltage transformer-rectifier, 100% duty cycle
Electrode wire	1⁄16-in.-diam E70S-3
Electrode holders (four)	Mechanized, fixed; air cooled
Wire-feed system	Variable speed, motor driven
Current	430 amp, dcrp
Voltage	27 v
Shielding gas	Carbon dioxide, at 35 cfh
Welding position	Horizontal
Number of passes	One
Wire-feed rate	245 ipm
Welding speed	50 ipm
Production rate	1000 pieces per hour, using four electrode holders

Fig. 33. Automotive-wheel assembly that was welded by the automatic gas metal-arc process for maximum fatigue resistance (Example 99)



Weld type	Single-flare bevel groove
Power supply	500-amp rectifier
Electrode wire	0.045-in.-diam E70S-3
Electrode holder	500 amp, air cooled
Current	240 amp, dcrp
Voltage	21 v
Shielding gas	Carbon dioxide, at 20 to 25 cfh
Welding position	Flat
Wire-feed rate	400 ipm
Welding speed	30 ipm
Arc time	6.5 sec per side
Floor-to-floor time	76 sec per part

Fig. 34. Machine used for automatic gas metal-arc welding of a spindle-arm assembly with welds on opposite sides, as shown (Example 100)

ensure accurate positioning of electrode wire. Each of the four legs was continuously lap fillet welded along its 4-in. outer edge.

The completed wheel assembly was visually and mechanically inspected for weld integrity and dimensional accuracy.

Example 100. Automatic Welding of Spindle-Arm Assembly (Fig. 34)

The automatic welding machine shown at the left in Fig. 34 was used for making two welds 2.90 in. long in a spindle-arm assembly (shown, together with joint details, at right in Fig. 34). This machine was one unit in a partly manual, partly automated production line that saved 3 lb of material and 2 hr total manufacturing time per piece in comparison with former methods. The savings of material and time resulted in a 25% reduction in over-all cost.

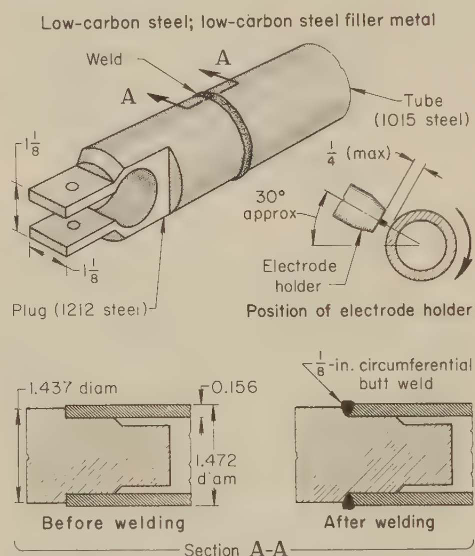
Arc welding equipment included a 500-amp rectifier with an automatic sequencer, a heavy-duty automatic wire feed, a heavy-duty air-cooled electrode holder, and a flowmeter for control of carbon dioxide shielding gas supplied from cylinders. The mechanical equipment provided for advance-retract motion of the electrode holder in the horizontal plane, rotation of the electrode holder in the vertical plane, and 180° rotation of the fixtured workpiece to present each joint in turn for welding, without reclamping (Fig. 34).

A control panel provided for regulation of welding current, wire-feed rate, and travel speed of the electrode holder, and had push buttons for starting and stopping gas flow, starting the automatic welding sequence, and controlling rotation and lateral motion of the electrode holder.

The machine required setting up of travel limits only for the first operation. Subsequent travel was initiated by a push button and terminated by interlock switches. The only manual operations after setup consisted in loading parts, swinging the clamping fixture 180°, pinning the fixture, and unloading the welded assembly.

Welding conditions are given in the table that accompanies Fig. 34. The sequence of operations was as follows:

1 With the electrode holder retracted, the two components were manually loaded in the fixture — the spindle being placed on the mandrel and the U-shape arm clamped in position against the spindle.
2 The electrode holder was rotated to a work angle 15° from the vertical.



Joint type	Circumferential butt
Weld type	Square groove
Power supply	250-amp, three-phase, constant-voltage rectifier
Electrode wire	0.035-in.-diam low-carbon steel
Electrode holder	Retractable, machine held, air cooled and operated
Wire-feed system	Fully automatic
Current	225 amp, dcrp
Voltage	22 v
Shielding gas	Carbon dioxide, at 5 to 10 psi (from cylinder)
Number of passes	One
Wire-feed rate	400 ipm
Production rate	112 pieces per hour(a)

(a) Production rate by the original method (semiautomatic gas metal-arc welding) was 58.2 pieces per hour.

Fig. 35. Fork-spring tube that was welded by the automatic gas metal-arc process to increase production (Example 101)

3 The start button was pushed, feeding the electrode holder forward and simultaneously starting gas flow, welding current, and wire feed. At the end of the weld traverse, current downsloped for crater fill; then wire feed and gas flow stopped. The electrode holder was rapidly retracted.
4 The fixture was manually pivoted 180°. The electrode holder was rotated to an opposite 15° work angle and the lateral slide was indexed to the new position. Operation 3 was then repeated.
5 The welded assembly was manually unloaded; the welds were snag ground, and the spindle was finish machined to size.

Total time cycle per side was 10.5 sec, and index time (for 180° rotation) was 10 sec, making total machine time per assembly 31 sec. Loading and unloading time was 45 sec, thus resulting in a floor-to-floor time of 76 sec per weldment.

Example 101. Use of Automatic Welding for Increased Production Rate and Better Appearance (Fig. 35)

The fork-spring tube shown in Fig. 35 was originally welded by the semiautomatic gas metal-arc process. When the process was fully automated except for loading and unloading, production rate was increased by 92.4% and less highly skilled workers were needed.

In preparation for welding, the two parts of each assembly were degreased and the plug was pressed into the tube. For automatic gas metal-arc welding, each assembly was manually loaded in a special chucking fixture in a horizontal position. The assembled tube and plug were rotated at a fixed speed during welding. The electrode holder was held in a retractable air-operated mechanism at 30° above the horizontal, as shown in Fig. 35. The weld was completed in one pass, and no preheat or postheat was necessary. Other conditions for automatic welding are given in the table that accompanies Fig. 35.

After welding, the workpiece was manually removed from the chucking fixture and turned in a lathe to remove excess weld metal, and the outside diameter was ground to finished size (1.4295-in. OD). The workpiece was then washed, zinc plated, and heated for 1 hr at 350 F.

All parts were inspected for weld appearance and straightness before they were sent to production assembly. It was essential that the welds have good penetration and be free of inclusions, and that the maximum curvature of the entire length of the workpiece be less than 0.003 in.

Example 102. Change From Shielded Metal-Arc to Automatic Gas Metal-Arc Welding of Axial-Flow Compressor Casings (Fig. 36)

A 30-in.-ID axial-flow compressor casing, 23 in. long, was built in two sections to simplify maintenance and reduce weight and cost. Each section consisted of a ribbed semicylindrical low-alloy steel forging (half of the casing) and two cast low-alloy steel flanges that were welded to the axial edges of the casing half (see Fig. 36). Nominal composition of the castings and of the forging was 0.20 C, 1.0 Cr, 1.0 Mo, and 0.10 V.

When the components were welded by the shielded metal-arc process, 20 hr (including 5 hr for weld repair) was required for completing one casing (welding four flanges to two casing halves). Changing to automatic gas metal-arc welding reduced welding time per casing to 2½ hr (this also included time for machine maintenance), and less time was needed for weld repair.

For automatic gas metal-arc welding, fixtures were designed so that both flanges were clamped to each casing half, thus ensuring good fit-up and reproducible final dimensions. Electromechanical relays controlled height and location of the electrode holder. Each flange was welded in two passes (see Fig. 36). For the root pass, the electrode holder followed the joint line (without being oscillated), and provided an average root penetration of ¼ in. The second pass was a fill pass, in which the electrode holder was oscillated to make a weld of two different widths, for outer and inner ribs; the welding current controlled the feed rate of the electrode wire. Additional welding conditions are given in the table that accompanies Fig. 36.

Weldments were inspected by visual and magnetic-particle methods. Despite the reduction in welding time and in the amount of weld repair needed, automatic welding presented three continuing problems: (a) weld porosity, resulting from nitrogen in the work metal; (b) maintenance of the automatic equipment; and (c) incomplete fusion, resulting from starting the welds on cold metal. Porosity caused by nitrogen in the work metal was prevented by subjecting the cast flanges to a 12-hr vacuum treatment at 1900 F prior to welding. The forged component did not require this treatment. Maintenance of equipment remained a problem, but the installation of numerically controlled equipment as a replacement for the electromechanical setup was expected to reduce maintenance costs. Incomplete fusion was minimized through careful selection of welding conditions, but it was not eliminated.

Timed Intermittent Welding

A portable gas metal-arc electrode holder with a nozzle-guide tube (see Fig. 37) can be used with a timer-controller to join sheets, plates, and bars in welded assemblies by intermittent (or "spot") fillet welds.

For timed intermittent welding, the parts to be joined are positioned and clamped together, or positioned in a welding fixture. The welder positions the electrode holder and initiates a preset timed sequence that starts the arc and feeds the wire. At the proper time, the arc and wire-feed automatically stop and the weld is completed. The electrode holder is then moved quickly to a new location, and the welding sequence starts over again. The size of the weld and the depth of penetration are determined by the arc time (expressed in cycles; 1 cycle equals 1/60 sec). The spacing of the welds is determined by the strength and rigidity of the design. Welds can be positioned as close as desired, but no closer than half the diameter of the nozzle-guide tube on the electrode holder. A typical application of timed intermittent welding is described in the next example.

Example 103. Timed Intermittent Welding of Motor-End Panels (Fig. 37)

Figure 37 shows a motor-end panel to which support bars and channel sections were "spot" fillet welded by timed intermittent gas metal-arc welding. As shown at the right in Fig. 37, the electrode holder had a nozzle-guide tube with a 45° bevel on opposite sides, so that when the tube was seated against two right-angled surfaces, the electrode holder was automatically positioned at a 45° angle from each of the two surfaces. For welding in the vertical position, as in this application, the electrode holder was lowered 15° from horizontal (see Fig. 37). A ceramic bushing was inserted over the guide tube. The end of the guide tube was preset for a 5/8-in. nozzle standoff. Welding conditions are given in the table accompanying Fig. 37.

In comparison with shielded metal-arc intermittent fillet welding, the method previously used for joining of these panels, the timed intermittent gas metal-arc process resulted in a 30% decrease in welding time and required less welder skill.

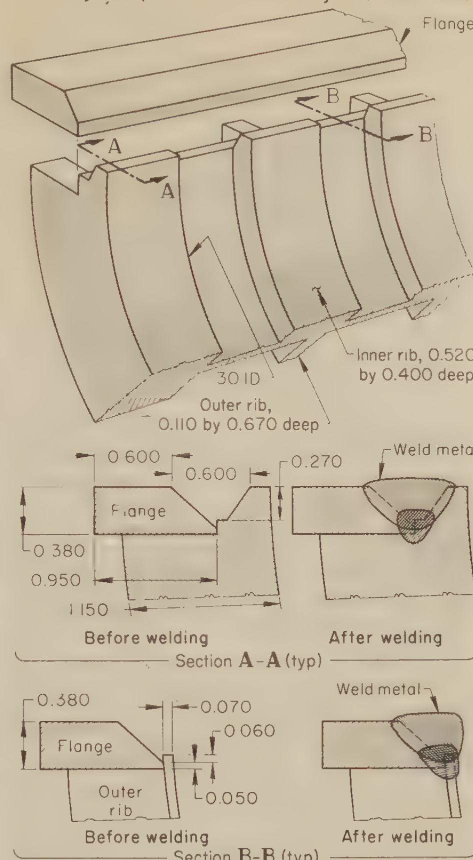
Common Causes of Difficulty

In gas metal-arc welding, with either a hand-held or a mechanically held electrode holder, production rate or weld quality, or both, may be impaired as a result of defective contact at the electrode tip (in the contact tube), erratic wire feeding, inadequate capacity of the wire-feed motor, faulty ground connection to the workpiece, and power fluctuation. These common causes of difficulty, together with methods of avoiding or correcting them, are discussed in the paragraphs that follow.

Contact-Tube Problems. Gas metal-arc welding depends on a transfer of current from a tip of copper or some low-resistance alloy to the electrode wire by means of a sliding contact within the contact tube.

Changes in resistance at this point will change arc voltage and, in turn, arc characteristics and may result in weld defects. The current density that must be passed across this point is higher than that used in other welding processes such as submerged-arc welding. Thus, small irregularities on the electrode wire, such as microscopic laps, seams and slivers, which would have little effect in submerged-arc welding, may significantly affect gas metal-arc welding. This effect increases in importance as electrode size decreases, and is more significant when welding alloys having higher resistance than carbon steel or low-alloy steel.

Residual drawing lubricants that have been allowed to remain on the electrode wire can result in a glazed condition within the contact tube and can increase the resistance to current passage. Electrode wire that has insufficient temper is a potential source of trouble, because the resulting low bearing pressure of the electrode within the contact tube can cause arc instability.

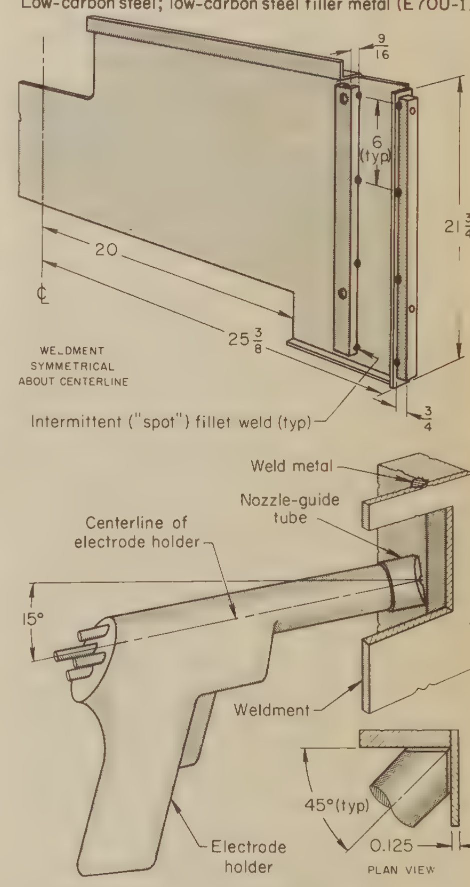


Conditions for Automatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Groove
Power supply	300-amp, 40-v rectifier, with variable inductance
Electrode wire	0.030-in.-diam(a)
Electrode holder	Mechanically held, water cooled
Wire-feed system	Automatically controlled
Current:	
Root pass	180 amp, dcrp
Fill pass	175 amp, dcrp
Voltage	32 v
Shielding gas:	
At electrode	75% argon – 25% carbon dioxide, at 30 to 40 cfh
Backing gas	Argon, at 40 to 50 cfh
Welding position	Flat
Number of passes	Two
Preheat and postheat	None

(a) 0.20 C, 1.0 Cr, 1.0 Mo, 0.10 V

Fig. 36. Partial view of a compressor casing, produced in two halves, for which a change from shielded metal-arc welding to automatic gas metal-arc welding decreased welding time and weld repair (Example 102)



Power supply	Constant-voltage rectifier
Electrode wire	1/16-in.-diam E70U-1
Electrode holder	Portable automatic, with constant wire-feed rate
Current	380 to 400 amp, dcsp
Voltage	30 v
Arc time, cycles	25(a)
Shielding gas	Argon plus 27% oxygen, at 14 cu ft per hour (measured by flowmeter)
Welding position	Vertical(a)
Bead size	1/4-in. fillet leg and 1/4 in. long(a)

(a) Electrode holder was stationary during arc time. On panels of other designs, welds were made in the horizontal position (with the electrode holder at 45° to joint), at an arc time of 35 cycles. These horizontal welds also had 1/4-in. fillet legs, but were 5/16 in. long.

Fig. 37. Motor-end panel (top) *in which "spot" fillet welds were made by timed intermittent gas metal-arc welding, using a portable electrode holder with a nozzle-guide tube, positioned as shown at bottom* (Example 103)

Erratic Wire Feeding. When small-diameter electrode wires are fed through relatively long flexible cables such as those used in semiautomatic gas metal-arc welding systems, sharp bends and turns in the cable can cause varying amounts of friction at these points, which in turn causes jumpy and erratic electrode-wire feed. This variation in friction can be significantly reduced by using lubricant-impregnated cable liners. Cable liners of nylon and teflon are also available. The use of cables and liners considerably larger in diameter than the electrode wire being used can also result in erratic feeding by allowing the wire to collapse or kink between the feed rolls and the contact tube.

Feed-roll slippage, a problem with some installations, can often be prevented by the use of knurled rolls, multiple rolls, or rolls designed to produce a locking taper with the wire.

Wire-Feed Motor Capacity. Some wire-feed systems have borderline torque capacity, which can cause variations in feeding rate. This is particularly prevalent in semiautomatic push systems, where there is a likelihood of varying torque requirements because of the frequent bending of the flexible cables. Wire-feed motors that have high torque capacity are therefore essential.

Power Fluctuations. In some critical applications, a sudden rise or fall of voltage in the main line supplying the welding power can cause difficulties, the severity of which depends on the type of welding being performed and the number of welding machines being supplied by the primary circuit. In most applications, power changes that occur over relatively long time periods will cause little trouble, since manual machine adjustments can compensate for them. However, wide power changes that occur because of high starting-power requirements of equipment on the same circuit can disrupt the equilibrium of the arc and increase the occurrence of defective welds. Any of three methods can effectively compensate for power fluctuation: (*a*) use of separate power-supply circuits that will not be susceptible to abrupt voltage swings for critical welding applications; (*b*) use of a motor-driven alternator or other type of line-voltage compensator between the power-supply line and the welding-power supply; and (*c*) use of welding-power supplies designed to provide line-voltage compensation.

Cost

Each application must be considered separately in selecting the most economical welding process. However, when an application is well adapted to gas metal-arc welding and when arc time is more than half of the floor-to-floor time, gas metal-arc welding usually costs less than shielded metal-arc welding.

In one plant, welding costs were studied for eight years. At the beginning of the study, approximately 85% of the welding was shielded metal-arc and 15% was gas metal-arc. At the end of the study only about 5% of the welding was shielded metal-arc and 95% was gas metal-arc. Results are shown graphically in Fig. 38. The upper curve in Fig. 38 shows that the average wage of welders increased about 65%. Despite this increase, total cost per pound of weld deposited decreased approximately 45% (lower curve). The fluctuation in cost of expendable welding materials (center curve) was caused in part by changes in the cost of shielding gas.

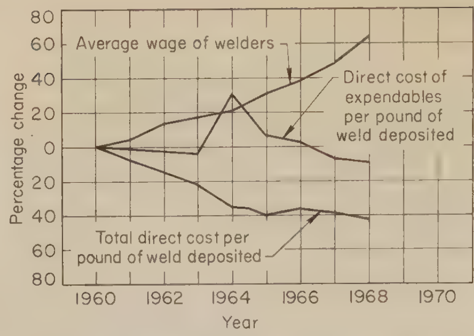


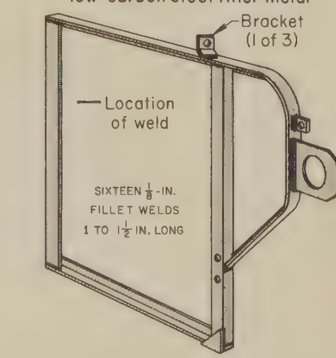
Fig. 38. Reduction in total welding cost, despite higher labor cost, by a gradual change from shielded metal-arc to gas metal-arc welding over eight years

Variables that can influence the cost of gas metal-arc welding, especially in the production of quantities of similar weldments, include the type of shielding gas used (see Examples 78 and 79), size of electrode wire (see Example 106), and joint design (see Example 81). Fit-up, because it affects arc time and welding speed, can also influence cost. Fit-up is generally more significant in gas metal-arc welding than in shielded metal-arc welding (see the section "Fit-up" on page 14 in the article on Shielded Metal-Arc Welding).

Table 7. Costs and Conditions for Gas Metal-Arc vs Shielded Metal-Arc Welding of a Radiator-Support Assembly (Example 104)

Item	Shielded metal-arc welding	Gas metal-arc welding
Cost per Foot of Weld		
Labor, at $2.50/hr	$0.1605	$0.0634
Overhead, at $5/hr	0.3210	0.1268
Electrode wire	0.0185(a)	0.0360(b)
Shielding gas	...	0.0046(c)
Total, per foot	$0.5000	$0.2308
Cost/lb of weld	$4.70	$2.17
Welding Conditions		
Electrode class	E6013	(d)
Electrode diam, in.	$\frac{5}{32}$	0.030, 0.035
Current, amp	240	120, dcrp
Voltage, v	27	20
Duty cycle, %	30	60
Shielding gas	...	CO_2
Shielding-gas flow	...	30 cfh
Welding speed, ipm	10.41	13.15
Welding time, hr/pc	0.4423	0.3000
Wt of deposit, lb/ft	0.106	0.106
Deposit efficiency, %	68	95

1010 steel, 0.059 to 0.119 in.; low-carbon steel filler metal



(a) At $0.12 per pound. (b) At $0.32 per pound. (c) At $0.01 per cubic foot. (d) Composition: 0.07-0.19 C, 0.90-1.40 Mn, 0.30-0.50 Si, 0.025 max P, 0.035 max S.

Production Examples. In Examples 104 and 105, which follow, welding costs were reduced by changing from other processes to gas metal-arc welding. In Example 106, costs for gas metal-arc welding were reduced by a change to a larger-diameter electrode wire.

Example 104. Change From Shielded Metal-Arc to Gas Metal-Arc Welding That Reduced Welding Cost by 54% (Table 7)

A cost comparison and time study of the welding of radiator-support assemblies for trucks showed that gas metal-arc welding was more economical and required less time than shielded metal-arc welding, under the conditions shown in Table 7. The assembly, which is also shown in Table 7, was of cold rolled 1010 steel sheet 0.059 to 0.119 in. thick and required 16 fillet welds that were 1 to 1½ in. long. It was tack welded together in both vertical and horizontal positions before welding, and then placed in the best position for final welding by use of a positioner.

The cost comparison, details of which are given in Table 7, showed that the total cost per foot of weld for shielded metal-arc welding was $0.50, compared with $0.23 for gas metal-arc welding (a saving of 54% in cost per foot).

The time study showed that welding time per piece was 0.300 hr for gas metal-arc welding, compared with 0.442 hr for shielded metal-arc welding. In one year, time saved on 3404 assemblies was 484 hr.

Example 105. Change From Submerged-Arc to Gas Metal-Arc Welding That Reduced Welding Cost by 34% (Fig. 39)

In the production of a low-carbon steel support-bracket assembly for a camshaft and chamber (see Fig. 39), two circumferential fillet welds were used to join one end of a machined tube to a bracket, and the other end to a flange.

Originally, after the components had been tack welded, the assembly was mounted in a welding lathe equipped with air clamps and an air-operated, adjustable-stroke tailstock, and the fillet welds were made by the submerged-arc process, under the conditions listed in the table with Fig. 39. Production rate was 23 assemblies per hour, or 10,000 per month. Hand repair of welds was required on 10% of the assemblies, because of difficulty in controlling the position of the electrode. Also, a dam was required for holding the flux in position (see Fig. 17 on page 58 in the article on Submerged-Arc Welding), and it was difficult to keep the flux clean.

To overcome these drawbacks, processing was changed to gas metal-arc welding, in which two specially designed machines, controlled by one operator, were used to weld both joints simultaneously. The use of gas metal-arc welding reduced weld repairs to ½%, reduced welding costs by 34% (see cost comparison in the table with Fig. 39), and increased production rate to 70 assemblies per hour, or 30,000 per month. Most of the cost saving resulted from a 50% decrease in setup time.

The machines for gas metal-arc welding were used with a welding lathe that had an air-operated tailstock. A quick-change dividing head was located on the tailstock so that the bracket and flange would have the proper angular relationship after the assembly was clamped together. Two electrode holders were positioned to make the two fillet welds simultaneously as the assembly was rotated in the lathe. A variable-speed drive was mechanically linked to both

the headstock and the tailstock. To prevent arc blow, clamping fixtures in the headstock and the tailstock were independently grounded.

All components were washed before being welded. The bracket was positioned on the headstock of the welding lathe and clamped, and the tube was inserted in the round hole in the bracket. The flange was mounted on the quick-change dividing head on the tailstock. When the tailstock was advanced, the flange was forced onto the tube, and the assembly was clamped together at the end of the stroke. Welding conditions are given in the table that accompanies Fig. 39.

Quality control of the assembly consisted of hourly visual inspection and weld-size measurement. Periodic metallurgical examination of sections cut from weldments determined the solidification characteristics of the weld metal.

Example 106. Increase in Electrode Size That Reduced Cost by Increasing Welding Speed (Table 8)

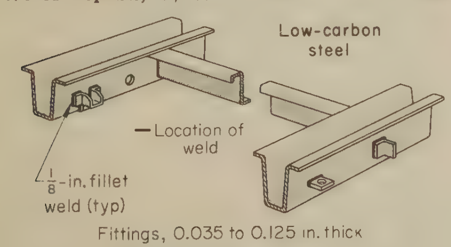
In gas metal-arc tack welding a truck-frame siderail subassembly (illustrated in Table 8), downtime was excessive because of *(a)* erratic contact and arcing in the electrode-holder contact tube; *(b)* soiled condition of the contact tube; *(c)* the use of a tapered nozzle, which increased the occurrence of arcing between the electrode wire and the contact tube; and *(d)* kinking of the electrode wire, which occurred because of its small diameter (0.035 in.) and because the cable assembly was located on the floor.

These faults were remedied by substituting a straight nozzle for the tapered nozzle; by locating the control box in an overhead position, so that the electrode wire could travel vertically to the electrode holder; and by using a larger-diameter (0.045-in.) electrode wire, which was stiffer and thus more resistant to kinking.

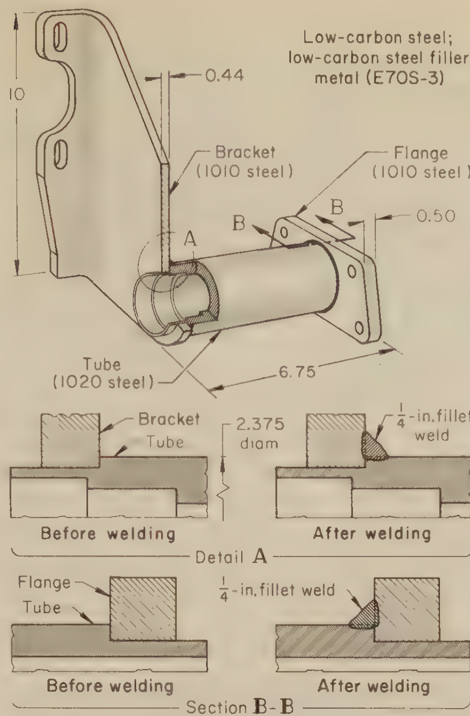
In addition to helping to reduce downtime, the change to the larger-diameter wire resulted in a 31% decrease in cost per foot of weld (see Table 8). This occurred because current input was increased to accommodate the melting (burnoff) characteristics of the larger wire, and the increase in current required an increase in welding speed, to avoid melt-through of the relatively thin steel sheet. Welding conditions employed with the two sizes of electrode wire are compared in Table 8.

Table 8. Cost Saving That Resulted From a Change From 0.035-In. to 0.045-In. Electrode Wire (Example 106)

Item	Diameter of wire, in. 0.035	0.045
Cost per Foot of Weld		
Labor, at $2.50/hr	$0.0634	$0.0423
Overhead, at $5/hr	0.1268	0.0846
Electrode wire	0.0084(a)	0.0107(b)
Shielding gas(c)	0.0046	0.0030
Total, per foot	$0.2032	$0.1406
Cost/lb of weld	$8.12	$3.92
Welding Conditions(d)		
Current (dcrp), amp	110 to 120	130 to 140
Voltage, v	18 to 20	25 to 27
Welding speed, ipm	13.15	19.70
Wt of deposit, lb/ft	0.025	0.036



(a) At $0.32 per pound. (b) At $0.29 per pound. (c) At $0.01 per cubic foot.
(d) The electrode wires of both diameters were of low-carbon steel (0.07-0.19 C, 0.90-1.40 Mn, 0.30-0.50 Si, 0.025 max P, 0.035 max S), and were used with carbon dioxide at 30 cu ft per hour. For both wire sizes, duty cycle was 60%, and deposit efficiency was 95%.



Item	Submerged-arc welding	Gas metal-arc welding
Cost per Assembly		
Electrode wire	$0.062(a)	$0.037
Shielding gas	...	0.043
Labor plus overhead	0.242	0.120
Total	$0.304	$0.200

Submerged-Arc Welding Conditions

Power supplies ......Two 400-amp, 40-v motor-generators(b)
Electrode wire 3/32-in.-diam EL12
Flux F70-EL12
Fixtures .....Welding lathe with air clamps(c)
Current ....300 amp, dc
Voltage ....25 v
Welding position ....Horizontal
Number of passes per weld ....One
Weight of deposit per assembly ......0.15 lb(d)
Flux consumption per assembly ....0.225 lb
Stickout ....1¼ in.
Welding speed ....19 ipm
Production rate ....23 assemblies per hour (10,000 per month)
Rejection rate (hand repairable) 10%

Gas Metal-Arc Welding Conditions

Power supplies ....Two 600-amp motor-generators(e)
Electrode wire ....5/64-in.-diam E70S-3(f)
Electrode holder ..400-amp rating, air cooled(g)
Wire feed ....Automatic, constant-speed push type
Fixtures ....Special welding lathe (see text)
Current and voltage:
Flange weld ....380 amp, dcrp; 28 v
Bracket weld ....320 amp, dcrp; 25 v
Shielding gas ...95% argon – 5% oxygen, 40 cfh
Welding position ....Horizontal
Number of passes per weld ....One
Wire-feed rate, flange weld ....162 ipm
Wire-feed rate, bracket weld ....144 ipm
Stickout ....1¼ in.
Welding speed ....19 ipm
Production rate ....70 assemblies per hour (30,000 per month)
Rejection rate (hand repairable) 0.5%

(a) Includes cost of flux. (b) Drooping-voltage type, with high-frequency start. (c) Lathe also had an air-operated, adjustable-stroke tailstock, and a 360°-indexing headstock clamp. An alignment fixture with a dividing head was used for tack welding components in proper angular position before final welding.
(d) 100% fill. (e) Constant-voltage type, with high-frequency start and stub-burnoff delay. (f) 0.24 lb consumed per assembly. (g) With automatic positioning and retraction.

Fig. 39. Assembly with two circumferential fillet welds that were made at less cost by gas metal-arc than by submerged-arc welding (Example 105)

Gas Metal-Arc Welding vs Alternative Welding Processes

The welding processes that are usually the most closely competitive with gas metal-arc welding for joining of carbon and alloy steels are shielded metal-arc welding, flux-cored arc welding, and submerged-arc welding. (These three processes are discussed in the articles that begin, respectively, on pages 1, 24 and 46 in this volume.)

Gas metal-arc welding is generally faster than shielded metal-arc welding, which is not readily adaptable to automatic welding. Shielded metal-arc welding, however, may be preferred for difficult-to-reach locations and for outdoor applications.

Flux-cored arc welding, which can be automated, is sometimes more economical than gas metal-arc welding, depending mainly on whether or not a shielding gas is used to supplement the shielding provided by the flux.

Examples of Improvements Obtained by Use of Gas Metal-Arc Instead of Shielded Metal-Arc Welding

The 14 examples that follow describe applications in which production rate was increased, weld quality was improved, or other benefits were obtained, by a change from shielded metal-arc welding to gas metal-arc welding. Other applications for which gas metal-arc welding proved superior to shielded metal-arc welding are described in Examples 85 and 104, in this article.

Example 107. Saving of 29% in Total Time

Lap and corner joints in various sizes and shapes of fuel tanks made of ⅛-in.-thick low-carbon steel required ⅛-in. fillet welds to be made in several positions. Originally, the tanks were shielded metal-arc welded, with 5/32-in. E6012 electrodes and 175-amp current, at a travel speed of 13 in. per minute.

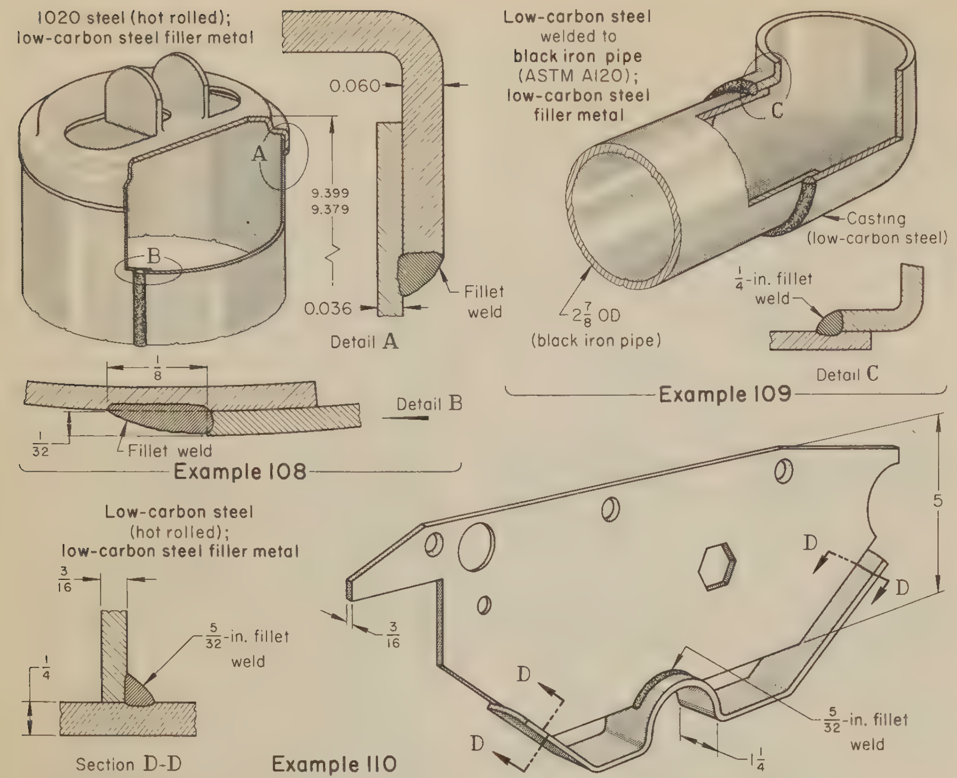
Subsequently, processing was changed to gas metal-arc welding. As a result, total time, including time for handling and cleaning, was reduced 29%, because in gas metal-arc welding:

1. Arc time was reduced 44.5%, because travel speed was increased from 13 to 25 in. per minute.
2. Time for cleaning was reduced because there was no slag to remove.
3. Amount of repositioning was reduced because gas metal-arc welding is more adaptable to multiple-position welding.

The gas metal-arc welding was done with 0.045-in.-diam electrode wire, fed at 240 in. per minute, with the power supply set at 20 volts. Shielding gas was a mixture of argon, at 15 cu ft per hour, and carbon dioxide, at 5 cu ft per hour.

Examples 108, 109, and 110. Reductions in Floor-to-Floor Time (Fig. 40)

Figure 40 shows three farm-equipment components — a filter housing (Example 108), an axle arm (Example 109), and a bracket (Example 110) — for which a change from shielded metal-arc to semiautomatic gas metal-arc welding resulted in savings in floor-to-floor time of 54%, 52%, and 58%, respectively. These savings significantly reduced production costs. Floor-to-floor times, together with welding conditions,



Welding condition	Example 108 (filter housing): Shielded metal-arc welding(a)	Example 108 (filter housing): Gas metal-arc welding(b)	Example 109 (axle arm): Shielded metal-arc welding(a)	Example 109 (axle arm): Gas metal-arc welding(b)	Example 110 (bracket): Shielded metal-arc welding(a)	Example 110 (bracket): Gas metal-arc welding(c)
Floor-to-floor time, min/pc ..	5.904	2.732	2.726	1.305	2.43	1.02
Electrode diameter, in.	1/8	0.035	3/16	0.045	3/16	1/16
Electrode material	E7014	Mild steel	E6012	Mild steel	E6012	Mild steel
Shielding-gas mixture, %	...	75 A, 25 CO_2	...	98 A, 2 O_2	...	98 A, 2 O_2
Shielding-gas flow rate, cfh ..	...	28(d)	...	25(d)	...	25(d)
Wire-feed rate, ipm	...	180	...	455	...	220
Arc time, min	3.661	1.032	1.364	0.589	1.11	0.482
Electrode consumption/pc ..	0.175 lb	0.049 lb	0.152 lb	0.120 lb	0.206 lb	0.092 lb

(a) With direct current from a motor-generator. (b) With direct current from a 500-amp rectifier, and heavy-duty wire feed. (c) With direct current from a constant-voltage rectifier, and automatic-arc wire feed. (d) From cylinders.

Fig. 40. Three farm-equipment components for which floor-to-floor time was reduced by a change from shielded metal-arc to semiautomatic gas metal-arc welding, under the conditions shown in table (Examples 108, 109 and 110)

are compared for the two processes and the three components in the table with Fig. 40. As this table shows, gas metal-arc welding also required less filler metal — mainly because it was not necessary to pile up filler metal to prevent melt-through.

Example 111. Doubled Production Rate, Despite Short Arc Time, for Welding Lugs to Plate

In the fabrication of a 3-lb cowl-support floorplate, four ¼-in. fillet welds ½ in. long and two ¼-in. fillet welds 1 in. long were required for attaching lugs to the plate (⅜-in.-thick low-carbon steel).

Originally, shielded metal-arc welding was used, and production rate was 16 floorplates per hour. When monthly production requirements increased from 400 to 1000 floorplates, the purchase of equipment for semiautomatic gas metal-arc welding was warranted. The change to gas metal-arc welding resulted in more than a twofold increase in production rate — to 34 floorplates per hour.

The large increase in production rate for a weldment of this type was unusual, because arc time per piece was only 20 sec. Because the weldment was light and could be quickly positioned by the use of a simple fixture, and because the joints were readily accessible, the ratio of arc time to setup and handling time was large enough to make semiautomatic welding practical. Elimination of deslagging (required for shielded metal-arc welding) contributed significantly to the increased production rate for gas metal-arc welding.

Example 112. Increase of 84% in Welding Speed, and Elimination of Repositioning (Fig. 41)

Figure 41 shows a fuel tank with a baffle fillet welded in place; both parts were of 0.150-in.-thick low-carbon steel sheet.

Originally, the assembly was shielded metal-arc welded, with 5⁄32-in. E6012 electrodes, but frequent repositioning of the work was required to obtain a maximum welding speed of 13.6 in. per minute.

When processing was changed to gas metal-arc welding, repositioning was eliminated, welding speed was increased 84%, and weld quality was improved. The assembly was positioned as shown in Fig. 41, and the ⅛-in. fillet welds were deposited at a welding speed of 25 in. per minute. No difficulty was encountered with the welds that had to be made in the vertical-down position. Little weld spatter was produced, and only minimum cleaning was required. Other conditions for gas metal-arc welding are given in the table with Fig. 41.

Example 113. Improved Weld Quality and Increased Production Rate (Fig. 42)

A 1⁄16-in. fillet weld 3⁄16 in. long was made in a corner joint on an electrical mounting base (see Fig. 42), which was subsequently zinc plated and chromate treated. Originally, the joint, which had a 1⁄32-in. root opening to simplify forming of the part, was shielded metal-arc welded, four workpieces being clamped onto a fixture for each setup. This arrangement made it difficult to locate the weld accurately, and as a result weld quality was poor. In addition, there was excessive weld spatter, which complicated the zinc-plating operation. Production rate, about 250 pieces per hour, was unsatisfactory.

A change to gas metal-arc welding, using a hand-held electrode holder, provided the following two improvements in technique.

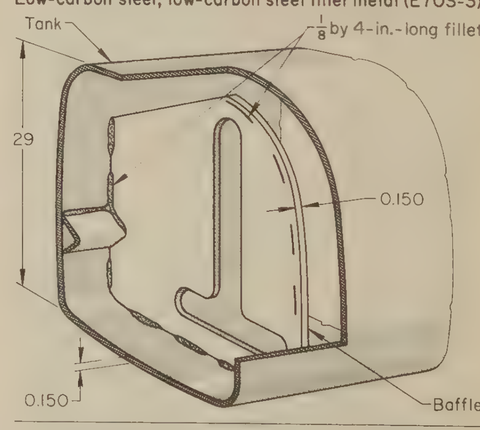
1 The electrode holder had a positioning guide, which facilitated locating the weld.
2 A new fixture (a simple rack type) that held ten workpieces and that eliminated clamping of the parts was constructed. Use of this fixture reduced loading and unloading time.

Figure 42 shows the electrode holder and fixture; the operating conditions for gas metal-arc welding are given in the table that accompanies Fig. 42. The simplified torch positioning eliminated false strikes and spatter, and improved weld quality. Locating time, welding time and loading time were reduced, and the improvement in production increased output to 643 pieces per hour.

Before welding, workpieces were degreased and loaded, ten at a time, into the fixture. As shown in Fig. 42, they were tilted 45°, which permitted the joint to be welded in the flat position and the electrode holder to be held vertical. The electrode holder, whose accessibility was limited by the adjacent flanges, was positioned on the first workpiece with the guide against the appropriate flange; it was then triggered and held during timed fillet welding. The procedure was repeated for the nine other workpieces in the fixture. Each weld was checked visually for loose weld spatter before the parts were removed from the fixture, and one part in each batch was checked with a pry bar to proof test the weld. If the weld was good, the test was nondestructive.

To maintain weld quality, the nozzle and the contact tube were cleaned at regular specified intervals. In addition, the settings of the welding machine and timer, the speed of the electrode wire, and the flow rate of the shielding gas were checked at least once every day.

Low-carbon steel; low-carbon steel filler metal (E70S-3)



Conditions for Gas Metal-Arc Welding

Joint type	T
Weld type	Fillet
Power supply	400-amp, constant-voltage rectifier
Electrode wire	0.045-in.-diam E70S-3
Current	225 ± 25 amp, dcrp
Voltage	23 v
Shielding gas	Carbon dioxide, at 30 cfh
Wire-feed rate	240 ipm
Welding speed	25 ipm

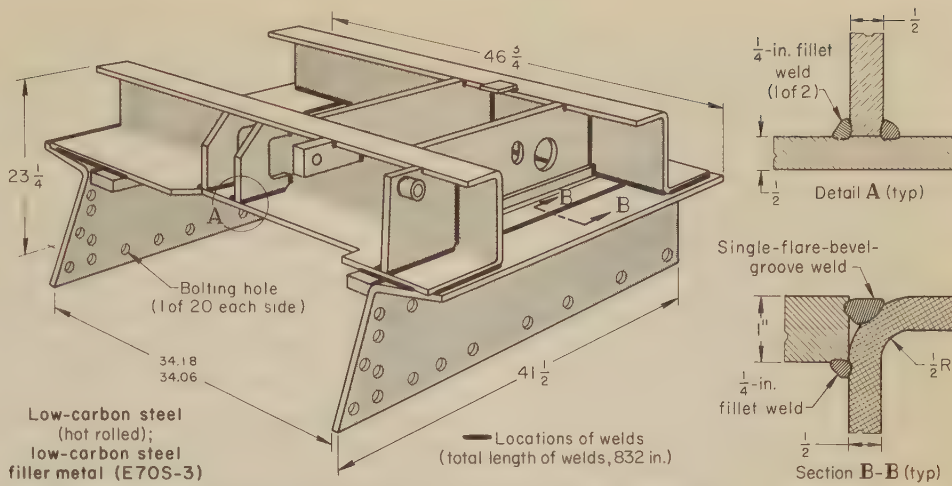
Fig. 41. Fuel tank and baffle for which a change from shielded metal-arc welding to gas metal-arc welding eliminated repositioning, increased welding speed 84%, and improved weld quality (Example 112)

Example 114. Reduction in Welding Time, Distortion, Weld Repairs and Cleaning Time (Fig. 43)

A 430-lb main base for a truck-mounted 15-ton winch was fabricated by welding components made from hot rolled low-carbon steel ½ in. and 1 in. thick, as shown in Fig. 43. The base was subsequently bolted to the truck frame through matching holes, which had been punched in the plates before forming. During forming and welding, opposing pairs of holes had to be kept aligned within a total tolerance of about 0.010 in., to facilitate subsequent use of a bridge reamer and insertion of bolts.

Originally, the base was shielded metal-arc welded with a 5⁄16-in. E7024 electrode, using 260-amp direct current from a rectifier. The components were in the mill-finish condition and had no edge preparation. Welding time per assembly was 13 hr. Two types of distortion occurred: (*a*) warping of mating surfaces, and (*b*) misalignment of bolting holes on assembly.

When semiautomatic gas metal-arc welding, with a spray arc, replaced shielded metal-arc welding, welding time per assembly was reduced to 10 hr, and faster welding resulted in less distortion. Also, weld repairs were minimized, and because of the absence of slag, cleanup time (chipping) per assembly was reduced by 30 min; electrode-drying ovens were not needed. Existing welding machines were used, although

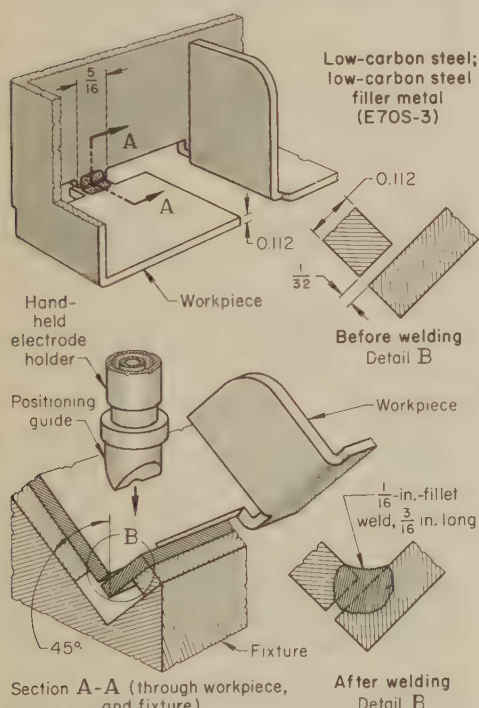


Conditions for Semiautomatic Gas Metal-Arc Welding

Joint types	Butt, corner, T, lap
Weld types	Groove, fillet
Power supply	300-amp, constant-voltage transformer-rectifier
Electrode wire	0.045-in.-diam E70S-3(a)
Electrode holder	Hand held, water cooled
Wire feed	Pull type, with dial control
Current	275 amp, dcrp
Voltage	28 v
Shielding gas	75% argon – 25% carbon dioxide, at 25 cfh(b)
Welding positions	Flat, horizontal
Number of passes	One
Welding speed	7 ipm
Welding time per assembly	10 hr(c)
Preheat and postheat	None

(a) Copper coated. (b) From cylinders; flowmeter controlled. (c) With shielded metal-arc welding, time per assembly had been 13 hr.

Fig. 43. Winch base for which a change from shielded metal-arc welding to semiautomatic gas metal-arc welding resulted in reductions in welding time, distortion (warping of mating surfaces and hole misalignment), weld repairs, and cleaning time (Example 114)



Conditions for Gas Metal-Arc Welding

Joint type	Corner, with 1⁄32-in. root opening
Weld type	1⁄16-in. fillet, 3⁄16 in. long
Power supply	200-amp, three-phase, constant-voltage rectifier
Timer	Variable, 0 to 60 cycles
Electrode wire	0.045-in.-diam E70S-3
Electrode holder	Hand held, air cooled(a)
Wire feed	Fully automatic, variable speed
Fixture	Rack type
Current	200 amp, dcrp
Voltage	24 v
Shielding gas	Carbon dioxide, at 35 cfh(b)
Welding position	Flat
Wire-feed rate	110 ipm
Welding time	22 cycles
Production rate	643 pieces per hour

(a) Timer controlled. Nozzle had a positioning guide (see drawing) to locate it in corner joint and against adjacent flange. (b) From cylinder.

Fig. 42. Electrical mounting base for which a change from shielded metal-arc to gas metal-arc welding improved weld quality and increased productivity (Example 113)

machine maintenance increased. Welding conditions are in the table with Fig. 43.

As before, the parts were welded in the mill-finish condition, without surface preparation. Subassemblies were welded on locating fixtures, to maintain alignment of the bolting holes. The fixture used for final assembly utilized the same holes for locating as were used in subassembly, to maintain proper hole locations. All assemblies were shot-blast cleaned after welding; chipping was sometimes needed.

The welders were certified according to the applicable military specifications, and there was constant visual inspection of work in process by qualified specialists.

Examples 115 and 116. Savings in Time for Welding, Straightening and Cleaning (Fig. 44 and Table 9)

The two low-carbon steel splash guards shown in Fig. 44 had to be clean and smooth for painting, and flat for attachment to a machine frame. After welding, the necessary flatness was obtained by rocking each weldment on a flat plate and straightening it with a hammer until rocking was negligible. Then the weldments were disk sanded and finish machined, before being painted and fitted to the machine frame.

Originally, these splash guards were shielded metal-arc welded, using an ⅛-in. covered electrode. Straightening time was excessive (see table with Fig. 44).

The process was changed to gas metal-arc welding, under the conditions listed in Table 9. As the comparisons in the table with Fig. 44 show, the change resulted in reductions in time for straightening to correct distortion, reductions in welding time (mainly because there were no interruptions for changing electrodes and for cleaning the weld to restrike the arc), and reductions in cleaning time (because slag removal was eliminated).

Example 117. Reduction in Welding and Cleaning Time (Fig. 45 and Table 9)

A sump tank, used for collecting lapping compounds, was produced from low-carbon steel by bending a sheet to a U-shape to form the long sides and sloping bottom, and then welding end panels, a splash plate, corner baffle, and fittings to the formed sheet as shown in Fig. 45. The major requirement, apart from leaktightness, was that the interior of the tank be relatively smooth, clean, and free of sharp corners and pockets. The splash plate and the corner baffle helped to promote circulation and to prevent the buildup of solids, as well as to simplify cleanout. Single-pass welds, as shown in the joint details in Fig. 45, provided satisfactory joints for all components.

Originally, the tank was welded by the shielded metal-arc process, using an ⅛-in. covered electrode. Total time per tank was 80 min, of which positioning and welding required 60 min, and cleaning and dressing of the welds required 20 min. Removal of slag from welds in the interior of the tank accounted for 4 min of the cleaning time, which was considered excessive.

When processing was changed to the use of gas metal-arc welding, under the conditions given in Table 9, total time per tank was reduced to 57 min — 42 min for positioning and welding, and 15 min for cleaning and dressing of the welds. The greatest portion of the 25% reduction in

Table 9. Conditions for Gas Metal-Arc Welding the Splash Guards and Sump Tank Shown in Fig. 44 and 45 (Examples 115, 116 and 117)

Power supply	300-amp, three-phase, constant-voltage rectifier, with variable slope control and variable inductance
Electrode wire	0.035-in.-diam E70S-3
Electrode holder	Hand held, 250 amp, air cooled
Wire feed	Push type, controlled speed
Current	160 amp, dcrp
Voltage	22 v
Arc type	Short circuiting
Shielding gas	Carbon dioxide, at 20 cfh (from cylinders, flowmeter controlled)
Number of passes per weld	One
Wire-feed rate	130 ipm
Stickout	5⁄16 in.
Welding speed	60 ipm
Joint penetration	25%

postweld cleaning time occurred because the interior of the sump tank required no cleaning following gas metal-arc welding.

Examples 118, 119 and 120. Reductions in Electrode Consumption, Arc Time and Floor-to-Floor Time (Fig. 46)

Figure 46 shows three 1020 steel weldments — a mast (Example 118), a bracket (Example 119), and a retainer (Example 120) — that, although varying widely in size, shape, and the amount of welding required, were designed for joining with 3/16-in. fillet welds.

Originally, shielded metal-arc welding was used, but to increase production rate, a change was made to semiautomatic gas metal-arc welding. As shown in the table with Fig. 46, the change resulted in reductions in electrode consumption and arc time, and floor-to-floor time was decreased by about 48% (Example 118), 29% (Example 119), and 43% (Example 120).

Before the change to gas metal-arc welding, flux-cored arc welding had been tried. Although floor-to-floor times and arc times were less than with shielded metal-arc welding (but by smaller percentages than the reductions obtained by gas metal-arc welding), the flux-cored arc process was not used because 1/4-in. fillet welds were the smallest that could be made in production.

Examples Comparing Gas Metal-Arc Welding With Joining Processes Other Than Shielded Metal-Arc Welding

The six examples that follow present comparisons of gas metal-arc welding with submerged-arc welding, oxyacetylene welding, gas tungsten-arc welding, resistance spot welding, braze welding, and copper brazing. For the applications described in these examples, gas metal-arc welding proved superior to the alternative process. Another application in which gas metal-arc welding gave improved results and lower cost is described in Example 105 (comparison with submerged-arc welding).

Example 121. Change From Submerged-Arc Welding to Gas Metal-Arc Welding for Faster Welding of Brake Drums (Fig. 47)

The 10-in. brake drum shown in Fig. 47, which is typical of a variety of brake drums for automotive passenger cars and light trucks, required two circumferential fillet welds at lap joints (identified as welds A and B in Fig. 47).

Originally, the joints were submerged-arc welded in separate operations. Then, processing was improved by submerged-arc welding both joints simultaneously, with increased current and voltage. This reduced welding time by 66%, but the cost per pound of weld, for electrode wire and flux, increased from \$0.24 to \$0.26.

A second improvement was to gas metal-arc weld both joints simultaneously. By this method, cost per pound of weld, for electrode wire and shielding gas, was reduced to \$0.15, and welding time was 31% less than that for the simultaneous submerged-arc welding.

The drum was made by centrifugally casting gray iron into the fabricated drum band and subsequently rough boring and facing the cast surfaces. Welding by all three procedures was fully automatic, and was done with machines built specifically for brake-drum welding. These machines advanced the preassembled cooling flange and drum band, positioned the drum back on the drum band, located the assembly for welding, rotated the assembly in a fixture during welding, and ejected the welded assemblies. Other welding conditions for the three procedures are included in the table accompanying Fig. 47.

After being welded, the brake drums were inspected visually for weld defects. Periodically, samples were sectioned to check weld penetration, weld soundness, and weld location.

Example 122. Change From Oxyacetylene Welding to Gas Metal-Arc Welding That Eliminated Finishing Operations and Reduced Welding Time by 39% (Fig. 48)

The center post and corner posts of a truck-windshield frame were joined to the sill, cowl and header by 1/32-in. fillet welds, as shown in Fig. 48. Good penetration was required in all welds, and limited weld buildup was essential to give a good finish for painting.

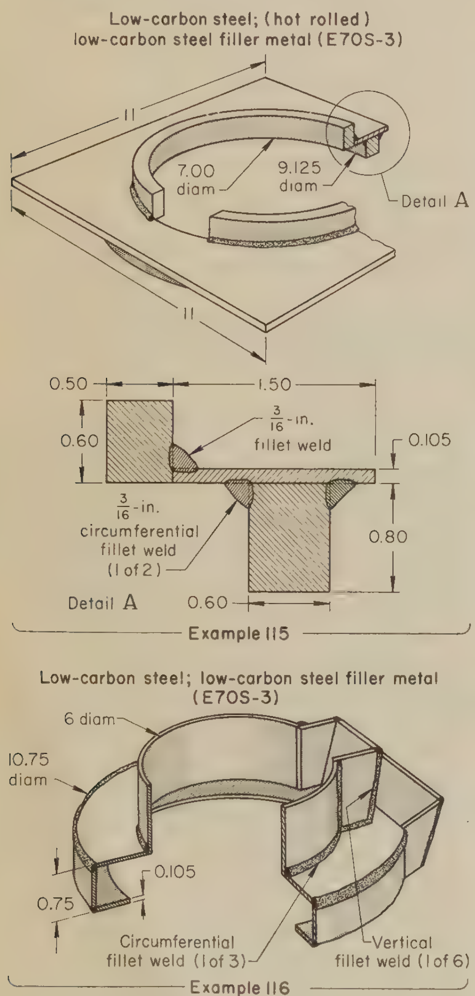
Originally, oxyacetylene welding was used, but grinding and abrasive blasting were required to produce a surface for painting.

When a change was made to semiautomatic gas metal-arc welding, the finishing operations were eliminated, welding time was reduced by 39%, and an over-all labor savings of 22% resulted. Rejection rate was less than 1%, and the rigidity of the assembly was increased 30%.

For gas metal-arc welding, the workpieces were manually loaded and clamped in a fixture before welding, and the assembly was removed by hand after welding; welding conditions are given in the table accompanying Fig. 48.

Example 123. Change From Gas Tungsten-Arc to Gas Metal-Arc Welding That Increased Production Rate and Decreased Rejection Rate (Fig. 49)

A link for an aircraft nose wheel had four bushings, a bolt stop and a bumper block welded to it, as shown in Fig. 49, and the welded assembly was subsequently



Operation	Time per weldment, minutes: Shielded metal-arc welding	Gas metal-arc welding
Example 115		
Positioning and welding	24	18
Inspection and straightening	18	3
Cleaning	4	1
Total time per weldment	46	22
Example 116		
Positioning and welding	35	27
Inspection and straightening	18	5
Cleaning	15	12
Total time per weldment	68	44

Fig. 44. Two splash guards for which a change from shielded metal-arc to gas metal-arc welding (under conditions listed in Table 9) resulted in less distortion, and in time savings (Examples 115 and 116)

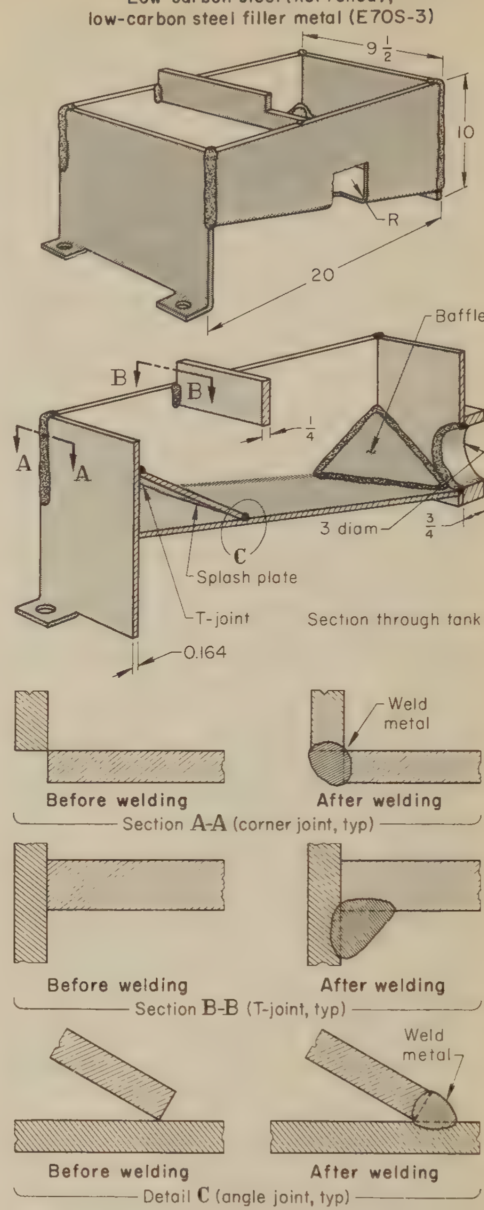
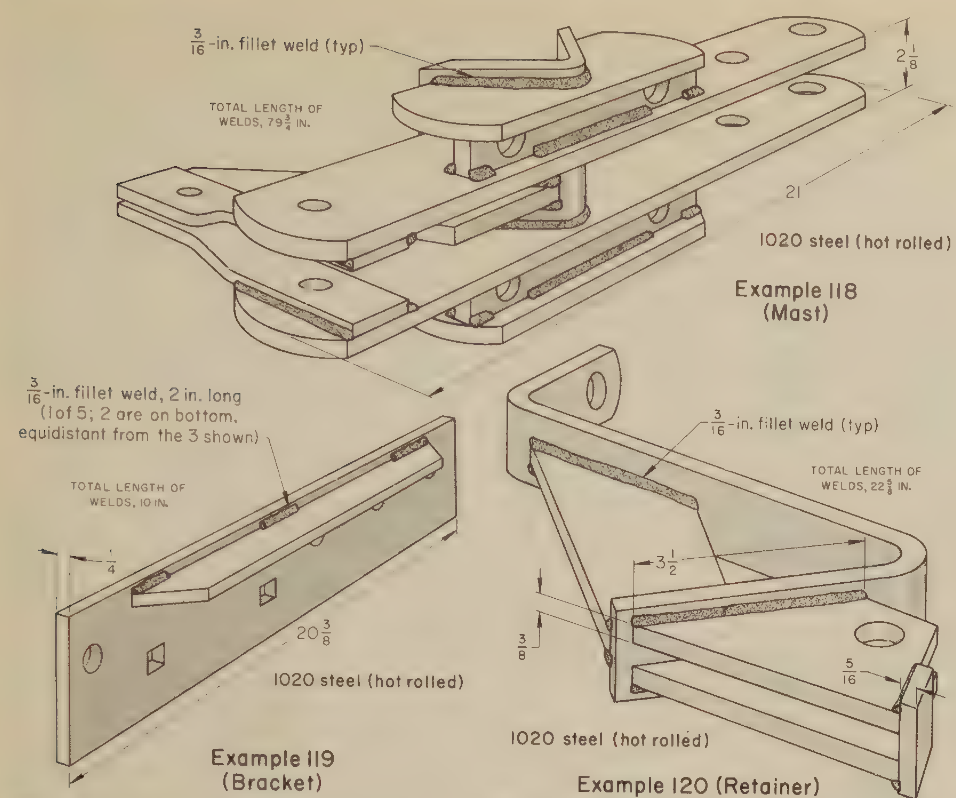


Fig. 45. Sump tank, and details of joints welded by the gas metal-arc process (under conditions listed in Table 9) in about 30% less total time than had been required for shielded metal-arc welding (Example 117)



Item	Example 118 (mast) Shielded metal-arc welding	Example 118 (mast) Gas metal-arc welding(a)	Example 119 (bracket) Shielded metal-arc welding	Example 119 (bracket) Gas metal-arc welding(a)	Example 120 (retainer) Shielded metal-arc welding	Example 120 (retainer) Gas metal-arc welding(a)
Current (dcrp), amp	120	290	190	290	140	290
Voltage, v	32	27	32	27	28	27
Electrode consumption, lb(b)	1.225	0.655	0.227	0.087	0.365	0.180
Arc time, min	9.040	3.307	1.248	0.439	4.060	0.911
Floor-to-floor time, min	19.042	9.916	2.140	1.521	6.655	3.793

(a) Shielding gas was a mixture of 98% argon and 2% oxygen, supplied from cylinders at 24 cu ft per hour. (b) Shielded metal-arc welding was done with E7018 electrodes ($\frac{5}{32}$ in. in Examples 118 and 119, $\frac{1}{8}$ in. in Example 120). In all three examples, gas metal-arc welding was done with 0.045-in.-diam E70S-3 electrode wire at a feed rate of 440 in. per minute.

Fig. 46. Three different weldments, joined by $\frac{3}{16}$-in. fillet welds, for which production time was reduced by changing from shielded metal-arc to semiautomatic gas metal-arc welding (Examples 118, 119 and 120)

fitted, aligned, reamed and straightened, before being magnetic-particle inspected.

Originally, the components, after being tack welded, were gas tungsten-arc welded, under the conditions listed in the table with Fig. 49. Production rate was 30 weldments per 8-hr day. In magnetic-particle inspection, 50% of the weldments were rejected and required weld repairs and subsequent realignment.

To increase production rate and reduce rejection rate, processing was changed to gas metal-arc welding, which did not require the tack welding operation necessary with gas tungsten-arc welding. Automatic tooling was used for the bolt stop and the bumper block. Conditions for gas metal-arc welding are given in the table with Fig. 49.

The production rate per day by gas metal-arc welding was 100 assemblies. Magnetic-particle tests of the first production run of 100 assemblies resulted in six rejected assemblies, but the defects were minor and no realignment was needed after weld repair. Also, fitting required was negligible, and reaming of the bushings was easier than after gas tungsten-arc welding.

With the gas metal-arc process, the ¼-in.-long bushings for the complete production run were welded first. For this step, a jig was bolted to a turntable. The electrode holder was held in place by a clamp on the arm, and handwheels were used to adjust it vertically, horizontally front to back, and horizontally left to right. Before welding, the bushing was nested in the jig through the link, and the link was fastened to the jig with a spring clamp. After the ¼-in.-long bushings had been welded, the jig was relocated to weld the ⅜-in.-long bushings.

The bumper block also was located by a jig. A pin was inserted through the end of the link containing the ⅜-in.-long bushings and a hole in the end of the welding jig. The bumper block was located by a hole in the face of the jig and the corresponding hole in the bumper block.

The bolt stops were located by placing a bolt in the bushing and placing the bolt stop against the bolt face. The bolt stop was then welded to the link and bushing.

Example 124. Change From Resistance Spot Welding to Gas Metal-Arc Welding for 60% More Production (Fig. 50)

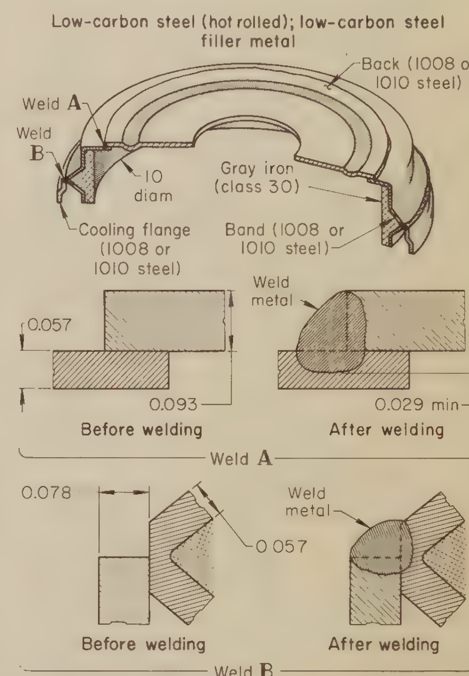
Figure 50 shows a sheave consisting of two matching components (of hot rolled, pickled and oiled low-carbon steel sheet, 0.135 in. thick) welded at an edge joint. The primary requirement of the welded joint was the provision of a solid backing for a belt pulley in fairly severe service.

Originally, the sheave components were joined by 16 resistance spot welds ⅜ in. in diameter, equally spaced around the periphery of the sheave (see left view in detail A, Fig. 50). Welds were satisfactory, but welding time per sheave was 1 min, and production rate was 32 sheaves per hour.

By changing to automatic gas metal-arc welding, under the conditions listed in the table with Fig. 50, welding time per sheave was reduced to 40 sec, and production rate was increased to 51 sheaves per hour. The gas metal-arc weld was a continuous weld along the periphery of the edge joint between the two components (see view at right in detail A in Fig. 50). During the gas metal-arc welding cycle, the operator was able to stack parts and to remove the small amount of weld spatter.

Example 125. Change From Braze Welding to Gas Metal-Arc Welding That Eliminated Failures and Reduced Cost by 50% (Fig. 51)

The welded joint between an upright support tube and a formed plate at the base of a single-pedestal overbed hospital



Item	Submerged-arc welding: Welds made separately	Submerged-arc welding: Welds made together	Gas metal-arc welding (welds made together)
Welding time per drum, sec	87(a)	29	20
Cost per pound of weld(b)	\$0.24	\$0.26	\$0.15
Welding Conditions(c)			
Current, amp:			
Weld A(d)	450	540	600
Weld B(d)	350	480	520
Voltage, v:			
Weld A	26	28	24
Weld B	25	27	23
Welding speed, ipm:			
Weld A	46	65	94
Weld B	45	71	105
Electrode wire	(e)	(e)	(f)
Shielding gas	...	...	CO_2(g)

(a) 41 sec for weld A, plus 46 sec for weld B. (b) Cost of electrode wire and flux, for submerged-arc welding; cost of electrode wire and shielding gas, for gas metal-arc welding.

(c) For all three methods, power supplies were 500-amp or 600-amp rectifiers or motor-generators, of the constant-voltage type; wire feeders had constant speed with slow approach, crater fill and burnback control; welding cycle was timer controlled in sequence with fully automatic loading, positioning, welding, and ejecting equipment; fixture had variable-speed rotation.

(d) Direct current; straight polarity for submerged-arc welding, reverse polarity for gas metal-arc welding.

(e) For weld A and weld B, $\frac{3}{32}$-in.-diam EM12K. (f) For weld A, $\frac{3}{32}$-in.-diam E70S-3; for weld B, $\frac{5}{64}$-in.-diam E70S-3. (g) At 45 cfh.

Fig. 47. Brake drum for which gas metal-arc was faster and cost less than submerged-arc welding for two circumferential fillet welds at lap joints (Example 121)

table (Fig. 51) had to resist overloads that resulted when the outboard edge of the table was improperly used as a seat. This eccentric loading subjected the weld to a force several times greater than the weight of the seated person.

Originally, the joint was manually braze welded, but weld failures resulted because the base metal was not always properly heated. Because cold joints were difficult to detect by visual inspection, an alternative welding process was needed. Flash welding was considered, but was rejected because the production volume, which was only 150 tables per day, was too small to warrant the cost of equipment and tooling; also, a flash-removal operation would have been required.

Semiautomatic gas metal-arc welding was selected to replace braze welding. This change virtually eliminated weld failures. Also, total welding cost was reduced by 50% (see cost comparison in the table with Fig. 51), less welder skill was required, and productivity was increased.

Welding conditions for both processes are included in the table accompanying Fig. 51. The sequence of operations was similar for both types of welding. The rectangular tube was deburred and sized, and was then assembled into the formed steel plate. The assembly was clamped in a simple fixture, to maintain squareness, and was welded in the position shown in section B-B in Fig. 51. No cleaning was required following welding, because the welded joint was hidden in the final assembly to the pedestal. A visual inspection was made of each weld to control quality.

Example 126. Change From Copper Brazing to Gas Metal-Arc Welding To Eliminate Distortion (Fig. 52)

The plate assembly shown in Fig. 52 (a cover for an electrical tank) consisted principally of a cover plate and a cup, both of 1008 or 1010 steel, and two 0.312-in.-diam rods of 1112 or 1113 steel, which were joined to the plate and the cup. The four joints were required to withstand an equally distributed 800-lb pull in the direction of the axis of the rods.

At first, the rods were joined to the plate and the cup by copper brazing, because an adapter and a fitting had to be brazed on the face of the plate not visible in Fig. 52, and thus all joining could be done in a single operation. Although the brazed joints had adequate strength, the high furnace temperature for copper brazing caused distortion that exceeded tolerances on parallelism and curvature (see Fig. 52) to the extent that 50 to 75% of the brazements were rejected.

Rejections because of distortion were eliminated by the use of gas metal-arc welding for the four rod joints and low-temperature soldering for the adapter and the fitting. In spite of the normally poor weldability of 1112 or 1113 steel — because of the relatively high phosphorus and sulfur contents — the rod welds had adequate strength. Although costs for the equipment and operators for gas metal-arc welding were higher, they were offset by the elimination of rejects due to distortion. The change from brazing to welding had no significant effect on the over-all production rate of the assembly.

Gas metal-arc welding was done in two steps. First, the rods were single-bevel-groove welded to the cup (see detail A in Fig. 52) in the flat position, then the assembly was turned completely over for plug welding (see detail B in Fig. 52). The only welding-operator attention required was to turn the assembly and position the joints under the electrode holder. Conditions for gas metal-arc welding, which were the same for the groove and the plug welds, are given in the table with Fig. 52.

Safety Practice

All bulk-gas installations should be made in conformance with National Fire Protection Association Standards 51, 565 and 566, and the usual handling requirements for high-pressure gas cylinders, hoses and regulators should be followed. When gas mixtures contain oxygen, the safety requirements for oxygen cylinders should be strictly observed. The correct regulator or flowmeter, or both, should be used for each gas. Traces of grease, oil or dirt in any of the equipment that is connected to an oxygen supply can cause a violent explosion.

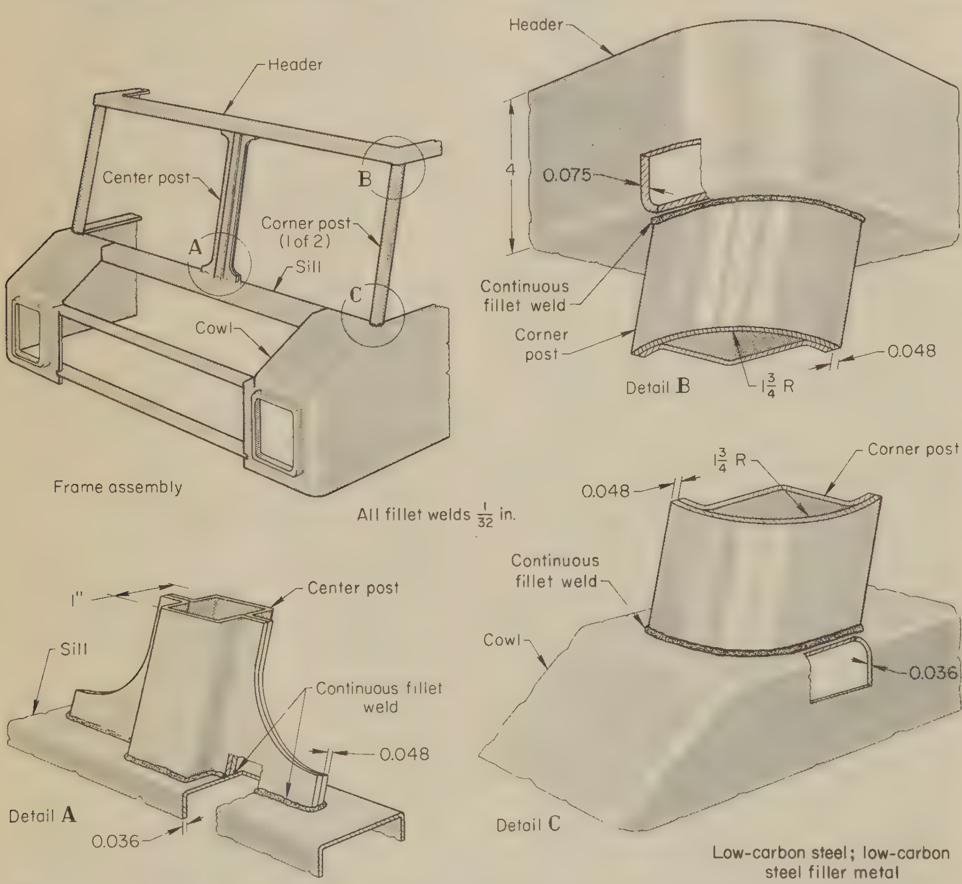
All welding machines should be securely grounded, to prevent accidental electric shock. Multiple-conductor line supply cables are recommended, especially for portable machines. Cables should be of sufficient size to carry the maximum current required. Insulation should be protected from cuts and abrasion, and the cable should not come in contact with oils, paints or other fluids, because deterioration may result. Damaged sections should be repaired or replaced without delay, and all connections should be tight, to prevent arcing or overheating.

Conventional fire-prevention requirements, such as removal of combustibles from the work area, should be followed. Fire prevention is particularly important when carbon dioxide is used for the shielding gas, because of danger of fire from weld spatter, which is frequently greater than when some other shielding gas is used.

Heat-resistant clothing and protective equipment are essential. For equivalent welding current, filtering lenses should be two to three shades darker than those used for shielded metal-arc welding, because the arc is brighter and ultraviolet radiation is more intense in gas metal-arc welding, especially when argon or helium is used. Depending on currents employed, lenses ranging in shade from No. 6 to No. 14 are recommended. Lenses that are too dark will cause eyestrain. For multiple-arc installations, flash goggles should be used.

Ventilation is always required, because oxygen is consumed, some ozone is generated, and toxic fumes from metal coatings or degreasing fluids may be present.

Zinc, cadmium, copper and lead coatings, and cleaning fluids such as any chlorinated compounds, should be removed before welding. The chlorinated

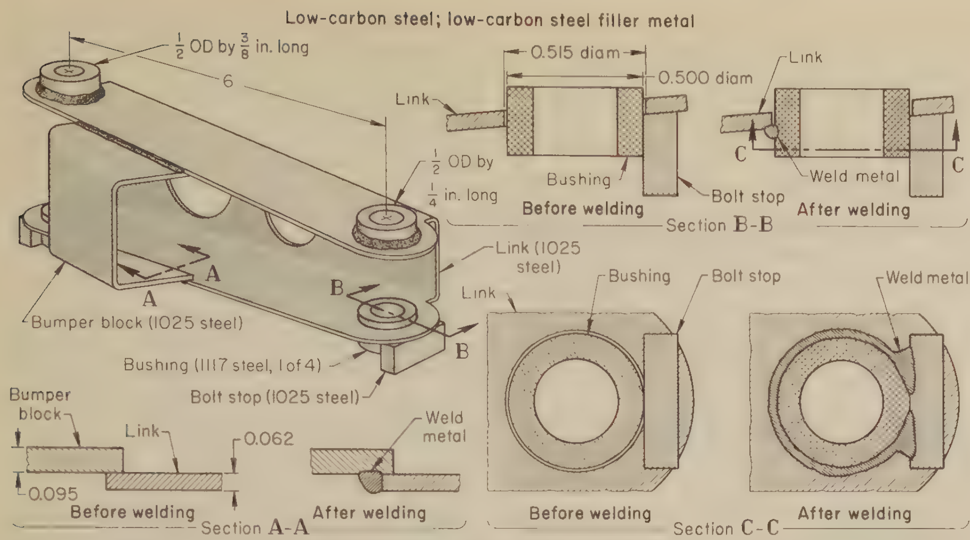


Conditions for Semiautomatic Gas Metal-Arc Welding

Joint type	T	Voltage	20 v
Weld type	Fillet	Shielding gas	75% argon – 25% carbon dioxide, at 20 cfh
Power supply	300-amp, single-phase rectifier	Welding position	Horizontal
Electrode wire	0.030-in.-diam low-carbon steel	Number of passes per weld	One
Electrode holder	Hand held; 60° head, short-arc tip	Wire-feed rate	230 ipm
Wire feed	Automatic, electromechanical	Welding speed	4⅜ ipm
Current	120 amp, dcrp	Welding time per assembly	9.05 minutes(a)

(a) Compared to 14.84 minutes per assembly by oxyacetylene welding

Fig. 48. Windshield-frame assembly for which a change from oxyacetylene welding to semiautomatic gas metal-arc welding eliminated finishing operations after welding and reduced welding time by 39% (Example 122)



Item	Gas tungsten-arc welding	Gas metal-arc welding(b)
Production, weldments per 8-hr day	30	100
Rejections requiring weld repair, %	50	0 to 6(a)
Welding Conditions		
Power supply	250-amp motor-generator	Transformer-rectifier(c)
Electrode wire	(d)	0.030-in.-diam E70S-2
Electrode holder	Manual, two types(e)	Air cooled(f)
Wire feed	Manual	Automatic, push type
Special equipment	Tacking jig	(g)
Current, amp	40 to 70, dcsp	300, dcrp
Voltage, v	10	20; 15(h)
Shielding gas	Argon, at 15 cfh	75% A – 25% CO_2, at 15 cfh
Welding position	.....	Flat
Number of passes per weld	One	One
Wire-feed rate, ipm	.....	223; 160(j)

(a) For lots of 100 assemblies. (b) Automatic, for welding the bushing to the link; semiautomatic, for welding the bumper block and the bolt stop to the link. (c) Constant-voltage type, with continuously variable slope. (d) Filler-metal wire was 1/16-in.-diam E70S-2, 36 in. long. (e) One was air cooled; one, water cooled. (f) Mounted, for automatic welding; hand held, for semiautomatic welding. (g) Adjustable torch holder; turntable; fixtures for assembly and clamping. (h) 20 volts for automatic welding; 15 volts for semiautomatic welding. (j) 223 in. per minute for automatic welding; 160 in. per minute for semiautomatic welding.

Fig. 49. Aircraft-wheel link for which a change from gas tungsten-arc welding to automatic and semiautomatic gas metal-arc welding of fillet welds at lap and T-joints increased production rate and reduced rejection rate (Example 123)

compounds and certain metals, such as cadmium, produce highly toxic gases under the influence of the arc. All cleaning done with volatile solvents should be isolated from welding operations, because fumes can travel a considerable distance, especially indoors.

If adequate ventilation is provided, carbon dioxide is not hazardous, even though it dissociates into carbon monoxide and oxygen in the arc. The carbon monoxide rapidly reoxidizes to carbon dioxide on cooling from arc temperatures. Tests show that the carbon monoxide concentration as close as 7 in. to the arc is not dangerous.

Careless acts such as placing the finger over the end of the welding gun to detect the electrode wire as it feeds through the contact tube, or placing the welding gun close to the ear to listen for the flow of shielding gas, should not be permitted.

Gas Metal-Arc Welding of Metals Other Than Low-Carbon Steel

Many metals other than low-carbon steel are commonly joined by gas metal-arc welding. Table 10 lists examples presented elsewhere in this volume that describe applications of gas metal-arc welding to various metals.

APPENDIX

Narrow-Gap Welding*

Narrow-gap welding is a gas metal-arc process, operating in the spray-transfer range of current densities, that was developed for making narrow welds in thick plate. The process employs a square-edge butt joint with a gap (root opening) ¼ to ⅜ in. wide, regardless of the plate thickness being joined. Feasibility studies have been conducted on steel plate up to 8 in. thick. The process is suitable for welding in all positions and has been used successfully on several carbon and low-alloy steels.

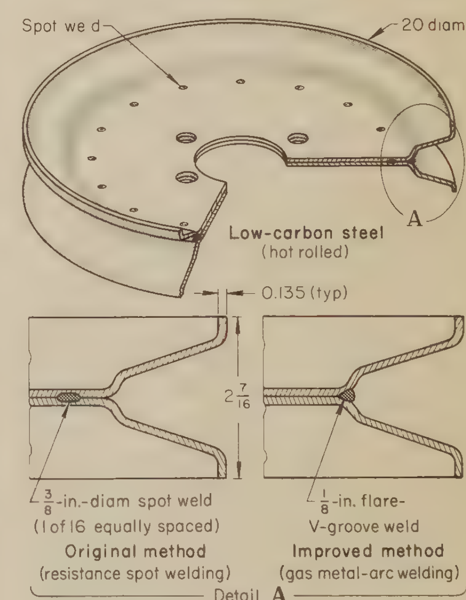
Advantages. Among the advantages claimed for narrow-gap welding are: (*a*) improved economy, because less filler metal is required for filling the joint; (*b*) good mechanical properties in the weld metal and the heat-affected zone, because the process entails relatively low heat input; (*c*) fully automatic operation in all welding positions, including overhead, when using spray-transfer welding conditions; and (*d*) improved control of distortion.

*Based on the article Narrow-Gap Welding — A Process for All Positions, by C. A. Butler, R. P. Meister and M. D. Randall, *Welding Journal*, Feb 1969.

Operating Principles. Narrow-gap welds are deposited by using special contact tubes that are inserted into the joint. In the preferred configuration, two contact tubes are used in tandem, and the electrodes are oriented so that one weld bead is directed toward one sidewall, and the other weld bead toward the opposite sidewall. Each contact tube is also guided so that it remains a fixed distance from its respective sidewall to assure proper sidewall fusion regardless of variations in gap width. Narrow-gap welding can also be done using a single contact tube centered in the joint. With this method, shielding gas is introduced into the narrow-gap joint from the plate surface by means of a special gas shield, and the weld is completed from one side of the plate.

Narrow-gap welds have been made with electrode wires ranging from 0.035 to 0.060 in. in diameter. Out-of-position narrow-gap welds are preferably deposited with the use of 0.035-in.-diam electrode wire.

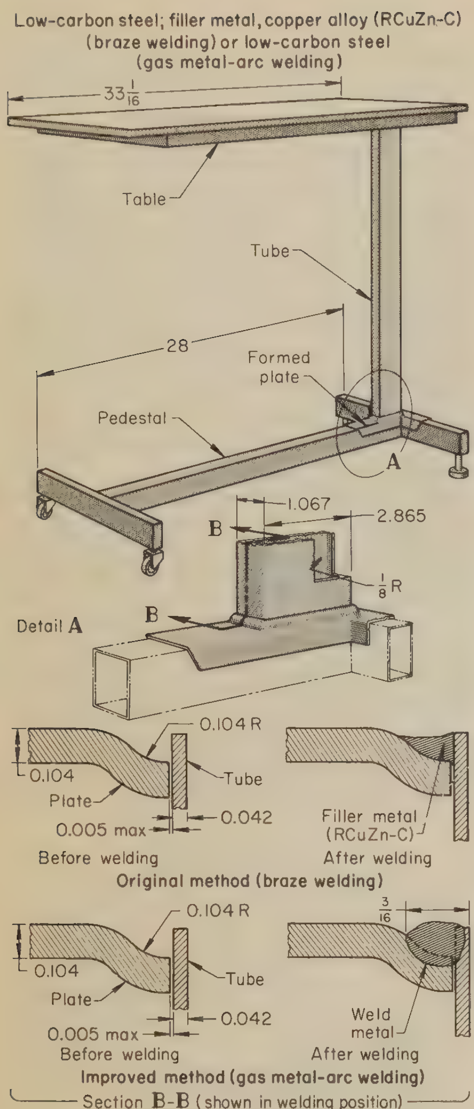
Relatively high travel speeds are used because of confinement imposed by the narrow-gap joint. If slower welding speeds were used, the weld puddle would become too large to control in the narrow gap. The weld beads obtained with the high travel speeds are thin and are deposited one on top of the other to fill the joint.



Automatic Gas Metal-Arc Welding	
Joint type	Edge
Weld type	Single-flare V-groove
Power supply ..	500-amp, constant-voltage type
Electrode wire	0.045-in.-diam E70S-3
Current	350 to 390 amp, dcrp
Voltage	31 to 33 v
Shielding gas	Carbon dioxide, at 20 cfh
Welding position	Workpiece axis 45° from horizontal; electrode holder at 2 o'clock
Wire-feed rate	600 ipm
Work-rotation speed	1½ rpm
Welding time per sheave	40 sec(a)
Production rate	51 sheaves per hour(b)

(a) Compared with 60 sec per sheave for spot welding. (b) Compared with 32 sheaves per hour for spot welding.

Fig. 50. Sheave for which production rate was increased 60% when automatic gas metal-arc welding replaced resistance spot welding (Example 124)



Item	Braze welding	Gas metal-arc welding
Comparison of Welding Cost per Assembly		
Material	\$0.035(a)	\$0.015(b)
Direct labor	0.075	0.040
Total	\$0.110	\$0.055

Conditions for Braze Welding

Torch .... Oxyacetylene, No. 53 tip(c)
Filler metal .... RCuZn-C
Flux .... Liquid proprietary mixture(d)

Conditions for Gas Metal-Arc Welding

Weld type .... Continuous fillet
Power supply .... 300-amp, three-phase, constant-voltage rectifier with slope control
Electrode wire .. 0.035-in.-diam low-carbon steel
Electrode holder .... Hand held, 150 amp, air cooled, light duty
Wire feed .... Push type
Current .... 90 amp, dcsp
Voltage .... 30 v
Shielding gas .... Carbon dioxide, at 22 psi (from cylinders)
Number of passes .... One
Wire-feed rate .... 320 ipm

(a) For filler-metal rod and flux. (b) For electrode wire and shielding gas. (c) Hand held; gas mixture adjusted to produce a slightly oxidizing flame. (d) Introduced to the flame by a gas fluxer. The mixture consisted of methyl alcohol, acetone and boric acid.

Fig. 51. Overbed table, and details of a continuous-weld T-joint at its base for which a change from braze welding to gas metal-arc welding eliminated failures and reduced cost (Example 125)

The first weld layer is deposited against a suitable backing. Approximately ten passes are required for each inch of plate thickness being joined. As a result, close control can be maintained over the composition of the narrow-gap welds.

Typical welding conditions used for welding steels with 0.035-in.-diam electrode wires are: 220 to 240 amp, 25 to 26 volts, electrode-wire feed rate of 560 to 625 in. per minute, travel speed of 40 to 45 in. per minute, and shielding gas consisting of a mixture of 80% argon and 20% carbon dioxide. These conditions provide a weld-heat input of about 7500 to 10,000 joules per inch per pass, for each electrode. A contact-tube-to-work distance of ½ in. is used. These conditions have been used for welding in the flat, horizontal, vertical and overhead positions.

The shielding gas used in narrow-gap welding depends on the metal being welded. For steel, an 80% argon – 20% carbon dioxide mixture is generally used. Premixed 75% argon – 25% carbon dioxide is also satisfactory.

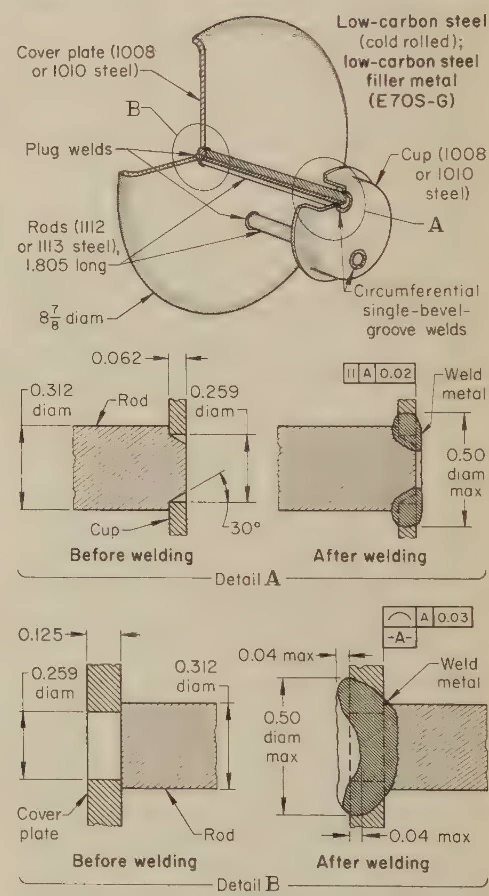
Welding Equipment. Most of the equipment required for narrow-gap welding is the same as that used for conventional gas metal-arc welding. Each of the two electrodes requires its own constant-voltage direct-current power supply, welding control panel, and electrode-wire feed motor. To meet the requirements of the process, however, some special items of equipment have been developed. These include special contact tubes and a means of guiding them in the narrow-gap joint, and various devices for providing efficient gas shielding.

Because the contact tubes are inserted into the narrow gap, they must be thin. Special water-cooled copper contact tubes have been developed that are only ⅛ in. thick. The cooling-water hoses and current conductor are attached directly to each contact tube so that the whole contact tube is electrically hot. The water cooling extends to the end of the contact tube. The full-length water cooling permits the use of Teflon for electrically insulating the contact tube from the sidewalls of the joint. A 0.030-in.-wall Teflon tube is used to insulate the contact tube, so that the total thickness of the insulated tube is about 3⁄16 in. The water cooling and the Teflon also minimize the amount of weld spatter adhering to the contact tube. The contact tube is equipped with a small tip, which can be replaced when it becomes worn or if a burnback occurs. The tip is electrically insulated by a ceramic shield that also serves to extinguish the arc before it reaches the water jacket of the contact tube if a burnback occurs.

With the contact tubes inserted into the joint, a special gas shield is used that rides above the surface of the plate and introduces the shielding gas into the joint from the plate surface. On laboratory-model narrow-gap welding units this is accomplished by mounting the gas shield on a free-floating shaft in the welding head that can move perpendicularly to the plate surface. The shaft is located over the narrow gap by a self-centering tapered guide roller that also maintains the gas shield at a fixed distance above the plate surface. A flexible skirt is used on the gas shield to seal the space between the gas shield and the plate surface. The gas shield is water cooled to prevent heat buildup when welding near the surface of the plates.

At each end the gas shield has special nozzles that produce a laminar flow of gas to prevent aspiration of air into the weld region. The gas-shielding system acts to force the shielding gas to go to the bottom of the joint to escape; as a result, aspiration of air into the weld region is eliminated. The gas coverage in the welding zone is excellent: in welds made at the bottom of 8-in.-thick plates in the flat and horizontal positions, the weld beads had a bright surface as-welded.

Positioning Equipment. When the contact tubes are inserted into the narrow-gap joint and the gas shield is in place, it is difficult to see the welding arcs. Therefore, it is necessary that the contact tube be positioned accurately with respect to the sidewalls and bottom of the joint, to prevent damage



Conditions for Gas Metal-Arc Welding

Weld types .... Circumferential single-bevel groove (detail A); plug (detail B)
Power supply .... 200-amp rectifier
Electrode wire .... 1⁄16-in.-diam E70S-G
Electrode holder .... 300 amp, water cooled
Fixtures .... Clamps
Current .... 200 amp, dcrp
Voltage .... 30 v
Arc starting .... High-frequency
Shielding gas .... Carbon dioxide, at 30 cfh
Welding time per weld .... 20 sec

Fig. 52. Plate assembly, and details of the joints for which a change from copper brazing to gas metal-arc welding eliminated distortion (Example 126)

resulting from accidental contact with the sidewalls and to ensure proper fusion into the sidewalls at all times. This is accomplished by seam-tracking and proximity-sensing systems, which permit fully automatic operation of the process by compensating for variations in joint gap width and weld fill. These systems also allow more latitude in joint fit-up and alignment of the welding head with the joint.

On laboratory model narrow-gap welding units, seam tracking is done by using floating welding heads and by loading the contact tubes against the sidewalls of the joint. The welding heads are mounted to enable them to adjust transversely to irregularities in the joint while remaining parallel to the joint. Tapered roller guides locate the welding heads over the center of the narrow-gap joint and also support the gas shield. The contact tubes are spring loaded against the sidewalls and are free to adjust transversely in the joint. The contact tubes are spaced from the sidewalls by shims placed between the insulation and the tubes.

The contact-tube-to-work distance is maintained constant by the proximity-sensing system. The welding-head electrode-drive motors and wire spools of laboratory model welding units are mounted on a vertical motorized slide that moves perpendicularly to the plate surface. The motion of the slide is controlled by a roller probe that rides directly on the weld surface. The roller probe is free to move perpendicularly to the plate surface and actuates limit switches as it follows the contour of the weld. The limit switches, in turn, activate the motorized slide so that it duplicates the contour of the weld surface, thereby maintaining a constant distance between the contact tube and the work.

Out-of-Position Welding. It is necessary to maintain the distance between the contact tube and the sidewalls of the joint constant within very close tolerances when welding out of position. The floating head and spring-loaded contact tubes alone are not sufficient, because of the normal variation in the amount and direction of the cast, or curvature, of the electrode wire along the length of a coil or from coil to coil. As the cast varies, the electrode position varies with respect to the sidewalls of the joint, so that it is difficult to maintain good sidewall fusion.

The problem is solved with narrow-gap welding equipment by using a controlled-cast wire-drive system. This system decreases the final cast diameter of the electrode wire below the as-received minimum diameter and maintains both the diameter and the direction of the electrode wire constant as it exists from the contact tube. This is accomplished by introducing the electrode wire into the drive rolls at 90° from the normal position so that the wire is formed around one of the drive rolls.

By orienting the drive rolls properly, the direction of the cast in the lead and trail electrode wires can be maintained 180° apart. One electrode then can be directed toward one side of the joint, and the other electrode can be directed toward the opposite side.

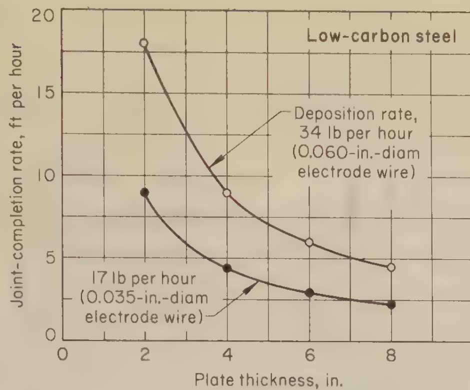


Fig. 53. Joint-completion rates for narrow-gap welding of various thicknesses of low-carbon steel plates at two deposition rates

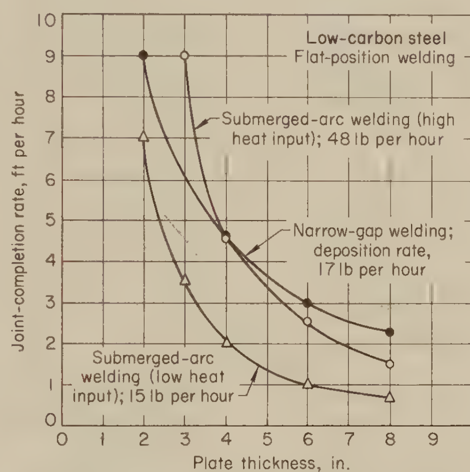


Fig. 54. Joint-completion rates for narrow-gap and submerged-arc welding of various thicknesses of low-carbon steel plates in the flat position

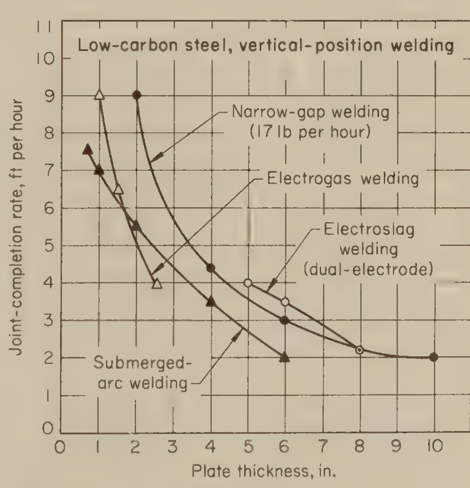


Fig. 55. Joint-completion rates for vertical-position welding of various thicknesses of low-carbon steel plates by the narrow-gap, submerged-arc, dual-electrode electroslag, and electrogas processes

Welding Applications. Narrow-gap welding systems have been proposed for both shop and field erection of large pressure vessels. One potential application, the narrow-gap welding of horizontal girth joints in large vertical steam generators, prompted a feasibility study, a part of which is described in the example that follows.

Example 127. Narrow-Gap Flat and Horizontal Welding of Steel Plates 6¾ and 8 In. Thick

As part of a feasibility study, narrow-gap welds were made in steel plates 6¾ and 8 in. thick, using a laboratory-model narrow-gap welding unit. The 6¾-in.-thick plates were of ASTM A302, grade B, steel (a manganese-molybdenum steel containing 0.20% C max, 1.15 to 1.50% Mn, and 0.45 to 0.60% Mo); the 8-in.-thick plates were of low-carbon steel. Welds in the A302 plates were made in the horizontal position; those in the low-carbon steel plates, in both the flat and the horizontal positions.

All welds were made using 0.035-in.-diam E70S-G electrode wire, and a mixture of 75% argon and 25% carbon dioxide as the shielding gas. Welding current at each of two electrodes was 260 to 270 amp at 25 to 26 volts. Welding speed, using special long contact tubes and standard gas shields, was 40 in. per minute.

Difference in plate thickness had no apparent detrimental effect on the quality of the welds. The weld beads had a bright silvery appearance, and macrosections indicated that weld soundness was satisfactory. Estimated joint-completion rate* at 100% arc operating factor was 2¾ ft per hour.

Joint-Completion Rates.* Figure 53 shows joint-completion rates for narrow-gap welding of various thicknesses of low-carbon steel plates at deposition rates of 17 and 34 lb per hour. The deposition rate of 17 lb per hour is obtained in all welding positions with the 0.035-in.-diam electrode wire normally used in narrow-gap welding of low-carbon steels or high-strength low-alloy structural steels. The 34-lb-per-hour deposition rate is obtained with larger wire (0.060-in. diam), and can be achieved only in flat-position welding.

Figure 54 compares joint-completion rates for narrow-gap welding of low-carbon steel plates with those obtained with two typical submerged-arc welding procedures. These comparisons are for flat-position welding, using a deposition rate of 17 lb per hour for narrow-gap and two deposition rates for submerged-arc — 48 lb per hour, for applications where heat-input control is not important, and 15 lb per hour, for applications where heat-input control is important. All of the curves are based on a 100% duty cycle. The submerged-arc data are for double-V grooves with a 45° included angle and a ¼-in. root face welded from both sides. The narrow-gap data are for welding from one side only. The data show that, for thicknesses greater than 2 in., narrow-gap welding compares favorably with submerged-arc welding.

Figure 55 compares joint-completion rates for vertical-position welding of low-carbon steel plates by the narrow-gap, submerged-arc, electrogas, and dual-electrode electroslag processes. Submerged-arc, electrogas and electroslag welding were done with ⅛-in.-diam electrodes. Spacing between plates was ¾ in. for electrogas welding, and 1 in. for submerged-arc and electroslag welding. All data in Fig. 55 are for 100% duty cycle. As these data show, for vertical-position welding, the joint-completion rates for narrow-gap welding are greater than for any of the other processes except dual-electrode electroslag welding (on 5-to-8-in. plate).

*Length of joint welded to full groove depth in one hour (also called joint-finishing rate).

Table 10. Examples of Gas Metal-Arc Welding That Are Presented in Other Articles in This Volume

Example	Base metal A	Base metal B	Filler metal	Current and voltage	Shielding gas	Essential subject of example(a)
			Carbon and Alloy Steels			
17	Low or medium-carbon steel	Same	Low-carbon alloy steel	90-110 amp; 17-19 v	75 A, 25 CO_2	Root pass, GMAW; filler passes, FCAW
69	Low-carbon steel	Same	E70S-5	325 amp, dcrp	60 A, 40 CO_2	GMAW vs FCAW vs SAW
367	ASTM A113	Same	E70S-2	375-425 amp, dcrp; 34-38 v	CO_2	GMAW vs electroslag welding
188	ASTM A120 (iron)	ASTM A181; 1020	E70S-2	170 amp, dcrp; 20 v	CO_2	Four welds in two operations
156	1045	...	ECuAl-A2	260-280 amp, dcrp; 24-27 v	Argon	Hard surfacing
187	1035	1045	Low-carbon steel	...	75 A, 25 CO_2	Joint design for penetration
190	1035-1050	Low-carbon steel	Low-carbon steel	75 amp, dcsp; 25 v	CO_2	Cost for four processes
191	0.45-0.55 C steel	Same	E70S-6	270 amp, dcrp; 28 v	95 A, 5 O_2	Change from SMAW and FCAW
192	High-carbon steel	Low-carbon steel	E70S-6	260 amp, dcrp; 29 v	95 A, 5 O_2	GMAW vs SMAW; costs
214	4130	Same	E70S-6	90 amp, dcrp; 18 v	CO_2	Bead-size control
215	4130	Same	Low-carbon steel	150 amp, dcrp; 20 v	CO_2	100% penetration; no cracks
162	4137H	...	WC granules in low-carbon steel	340-360 amp, dcrp; 29-32 v	Argon	Cost comparison for surfacing, using four processes
164	4140	...	H12 tool steel	250-400 amp, dcrp; 28-32 v	A, 1-2 O_2	Hard facing cutting edges
217	4140	1146	Low-carbon steel	160 amp, dcrp; 19 v	CO_2	Semiautomatic vs automatic
189	4617	1030 steel forging	Copper-coated low-carbon steel	225 amp, dcsp; 25 v	CO_2	Semiautomatic vs automatic; production rate
205	H11 tool steel	Same	H11 steel	460-470 amp, dcrp; 30.4-30.6 v	98 A, 2 O_2	Joint and welding conditions; GMAW vs GTAW
163	H12 tool steel	...	H12 (mod) steel	110 amp, dcrp; 22-24 v	...	Facing forging die cavity
216	ASTM A213, gr T11 (1.25 Cr, 0.5 Mo)	Same	1.25 Cr, 0.5 Mo steel	175 amp, dcrp; pulsed; 23 v	98 A, 2 O_2	Change from SMAW for clean, high-quality welds
197	A242	Same	E70S-3	300 amp, dcrp; 26 v	Argon	Less rigid part; fewer cracks
219	ASTM A302, gr B	Same	ERNiCrFe-5	...	Argon	Surfacing
218	ASTM A553, gr A (9% Ni steel)	Same	Inconel 625 (mod)	90-130 amp, dcrp; pulsed; 18-23 v	85 A, 15 He	Cost and welding conditions for GMAW and SMAW
			Cast Irons			
233	Gray iron	Low-carbon steel	Low-carbon steel	150 amp; 25 v	96 A, 4 O_2	Low-hardness weld
236	Ductile iron	1010 and 1025	E70S-G	200 amp, dcrp; 26 v	75 CO_2, 25 A	GMAW vs SMAW; production
237	Ductile iron	Same	Nickel-iron alloy	200 amp, dcrp; 26 v	Helium	Preheat reduces cracking
239	Pearlitic malleable iron	Low-carbon steel	Low-carbon deoxidized steel	200 amp, dcrp; 28 v	Argon-CO_2	Welds cleaner, fewer cracks; welding faster; vs SMAW
240	Ferritic malleable iron	Low-carbon steel	E70S-6	140 amp, dcrp; 23 v	CO_2	Fatigue-test results; welding conditions
			Stainless Steels			
264	Type 303	1020 steel	ER308L	Spray, 200-225 amp; pulse, 110-115 amp	98 A, 2 O_2	Spray-arc vs pulsed-arc metal transfer
266	Type 304	Same	ER308	85-95 amp, dcrp; 14-15 v	90 A, 7½ He, 2½ CO_2	Full penetration in sheet 0.045 in. thick
265	Type 321	Same	ER347	24¾ v	90 A, 7½ He, 2½ CO_2	Oxyacetylene welding to GTAW to GMAW
			Heat-Resisting Alloys			
278	Inconel 600	Same	ERNiCrFe-5	...	Argon	Weave-technique change
279	Inconel 600	Same	ERNiCrFe-5	275 amp, dcrp; 29 v	Argon	Manual welding
283	HK-40	Same	HK-40	...	Argon-CO_2	Root pass, GTAW
			Aluminum Alloys			
295	2014-T6	Same	ER4043	215 amp, dcrp; 28 v(b)	75 He, 25 A	Reducing width of HAZ
299	5014-O	6063-T42; 6061-T1	ER5356	190, 200 and 290 amp, dcrp; 24 and 25 v	Argon	Three welds at one time on pressure cylinder
302	5052	6063	ER4043	115 amp, dcrp; 20 v	Argon	Replacing riveting
296	5083-H	Same	ER5183	470 amp, dcrp; 35 v	75 He, 25 A	Welding pipe from both sides
300	5083-H11	Same	Alloy 5056	260 amp, dcrp; 12 v 375 amp, dcrp; 20 v	Argon	Semiautomatic and automatic welding of girders
304	5083-H11	Same	Alloy 5056	265 amp, dcrp; 25 v	Argon	Transverse joints in girders
308	5083-H32	6061-T6	Alloy 5056	610 amp, dcrp; 32 v	Argon	Spot welding sheets to frame
307	5083-O	Same	ER5183	300 amp, dcrp; 32 v	75 He, 25 A; 99 A, 1 O_2	Plate repair using a plug
297	5086	Same	ER5356	220 amp, dcrp; 26 v	Argon	Use of backing strips
305	5086-H32	5083-H112; 6061-T6	ER5356	160-180 amp, dcrp; 18-20 v	Argon	GMAW vs GTAW
306	5254	Same	Alloy 5254; ER5356	180-200 amp, dcrp; 27-27½ v	75 He, 25 A	Joining 2 forgings, tube, partition in 3 operations
309	6061	Same	ER4043	325 amp, dcrp; 28 v	75 He, 25 A	Spot welding stiffener to panel
322	6061	Same	ER4043-H18	Dcrp; 40 v	Argon	GMAW vs GTAW
303	6061-T4	6061-T6	ER4043	110 amp, dcrp; 19 v	Argon	Welding sheet to extrusions
294	6061-T6	Same	ER5154; ER5356	130 amp, dcrp; 24 v	Argon	Self-aligning extrusions
301	6061-T6	Same	ER4043	95 amp, dcrp; 17 v	Argon	Dust-tight covers
298	6351-T4	Same	ER5254	200 amp, dcrp; 20 v	Argon	Automatic welding
			Copper Alloys			
334	Alloy 175	Same	Alloy 175	325 amp, dcrp; 22 v	Argon	Weld condition
336	Alloy 613	Low-carbon steel	ECuAl-A2	320 amp, dcrp; 30 v	70 A, 30 He	Composition vs weldability
335	Alloy 614	Propeller bronze	ECuAl-A2	425 amp, dcrp; 35 v	Argon	Jacket welded to casting
337	Alloy 715	Same	ECuNi	145 amp, dcrp; 21 v 230 amp, dcrp; 28 v	50 A, 50 He 75 A, 25 He	Semiautomatic and automatic butt welding
			Magnesium Alloys			
339	ZE10A-H24	Same	ERAZ61A	135 amp, dcrp; 26 v 175 amp, dcrp; 17 v	Argon	Globular vs short-circuiting metal transfer
			Nickel Alloy			
354	Monel	Nickel-plated steel	ERNi-3	125 amp, dcsp; 22 v	Argon	Replaced SMAW

(a) FCAW = flux-cored arc welding; GMAW = gas metal-arc welding; GTAW = gas tungsten-arc welding; SAW = submerged-arc welding; SMAW = shielded metal-arc welding; HAZ = heat-affected zone. (b) Also 140 amp, dcrp; 30 v.

Gas Tungsten-Arc Welding (TIG Welding)

*By the ASM Committee on Gas Tungsten-Arc Welding**

GAS TUNGSTEN-ARC WELDING (often called TIG welding) is an arc welding process in which the heat is produced between a nonconsumable electrode and the work metal. The electrode, the weld puddle, the arc, and adjacent heated areas of the workpiece are protected from atmospheric contamination by a gaseous shield. This shield is provided by a stream of gas (usually an inert gas), or a mixture of gases. The gas shield must provide full protection; even a small amount of entrained air can contaminate the weld.

Applicability

Gas tungsten-arc welding is adaptable to both manual and automatic operation, and can be used to produce continuous welds, intermittent welds (sometimes called skip welds), and spot welds. Because the electrode is nonconsumable, a weld can be made by fusion of the base metal without the addition of filler metal. A filler metal may be used, however, depending on the requirements that have been established for the particular joint.

Gas tungsten-arc welding is an all-position welding process, and is especially well-adapted to the welding of thin metal — often as thin as 0.005 in.

Metals Welded. The nature of the gas tungsten-arc welding process permits its use for welding of most metals and alloys. Metals that are gas tungsten-arc welded include carbon and alloy steels, stainless steels, heat-resisting alloys, refractory metals, aluminum alloys, beryllium alloys, copper alloys, magnesium alloys, nickel alloys, titanium alloys, and zirconium alloys.

Lead and zinc are difficult to weld by the gas tungsten-arc process. The low melting temperatures of these metals make control of the process extremely difficult. Zinc boils at 1663 F, which is far below the arc temperature, and poor welds result from vaporization of the zinc. Steels and other metals that melt at higher temperatures, but that are coated with lead, tin, zinc, cadmium or aluminum, are weldable but require special procedures.

Welds in coated metals are likely to have low mechanical properties, as a result of interalloying. To prevent interalloying in welding coated metals, the coating should be removed in the area to be welded, then repaired after welding.

Base-Metal Thickness. Gas tungsten-arc welding is applicable to a wide range of base-metal thicknesses. The process is well adapted to welding sections ⅛ in. thick or less, because of the intense, concentrated heat produced by the arc, which results in high welding speeds. Multiple-pass welding with the addition of filler metal can be done.

For base metal more than ¼ in. thick, other welding processes are generally used, although multiple-pass gas tungsten-arc welding is used for thick sections in applications where high quality is mandatory (as in aerospace work). For example, in the fabrication of a 26-ft-diam rocket-motor case with a 0.600-in. wall, longitudinal and girth welds were made by the gas tungsten-arc process, using multiple passes and filler metal. Although a slow process for metal of this thickness, gas tungsten-arc welding was used because high-quality welds were mandatory.

The gas tungsten-arc process has been successful in welding various alloys in foil thickness. Thin sheet requires accurate fixturing, and for metal of foil thickness, machine or automated welding is necessary. Plasma-arc welding, often considered as a variation of gas tungsten-arc welding, has advantages for welding thin metal (see the article on Plasma-Arc Welding, which begins on page 138).

Workpiece Shape. Manual welding is required where complex shapes preclude the use of automatic methods. Manual torch manipulation is generally used for irregularly shaped parts that require short welds, or for welding in difficult-to-reach areas. Welds can be made manually in the flat, horizontal, vertical, and overhead positions.

Automatic equipment lends itself to curvilinear and rectilinear surfaces. It has been used for special sine-wave welding of corrugated titanium to stiffeners on both ends. For this sine-wave type of weld, a mechanical tracing unit has been designed that follows a template to guide the torch. Manual control of such a weld would be extremely difficult.

Fundamentals of the Process

Because in gas tungsten-arc welding the heat is produced between the electrode and the work, edges of the workpieces are melted and are joined as the weld puddle solidifies.

To obtain welds of good quality by the gas tungsten-arc process, it is essential that all surfaces to be welded and adjacent areas be clean. Filler metal, if used, must also be clean.

Further, it is essential that the components of the assembly being welded be held firmly in the correct position relative to one another. Fixturing is necessary when fit-up is marginal, work metals are thin, shapes are complex, welding is done without filler metal, or automatic welding is used.

Arc Initiation. Some preliminary means of initiating emission of electrons and ionization of the gas is generally used for initiating (striking) the arc. Energy for this emission and ionization can be obtained by touching the energized electrode to the work and quickly withdrawing it to the desired arc length by the use of a pilot arc, or by the use of auxiliary apparatus that produces a high-frequency spark between electrode and work. Mechanical retraction of the electrode from the work is limited to mechanized welding with a direct-current power supply. Pilot arc starting, however, is applicable to both manual and mechanized welding, but is similarly limited to use with direct-current power supplies as is mechanized retraction of electrodes. High-frequency spark starting is applicable to manual welding with either alternating or direct-current power supplies. Many power supplies incorporate an apparatus that produces a high-frequency spark to initiate and stabilize the arc.

When beginning to weld, if the electrode is started (or "warmed") on a piece of copper, the arc may be started on the work metal with greater ease. Prewarming also reduces the amount of tungsten that may be lost as the result of forcing the tip of a cold electrode to support maximum current.

An ultraviolet-ray lamp, aimed at the torch tip, was used to facilitate arc initiation in Example 137.

Electrode and filler-metal positions in manual gas tungsten-arc welding are shown in Fig. 1. Once the arc is started, the torch is held so that the electrode is positioned at an angle of about 75° to the surface of the workpiece and points in the direction of welding, as shown in all views in Fig. 1. To start welding, the arc usually is moved in a circular fashion until enough base metal melts to produce a weld puddle

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The assistance of E. B. LaVelle in the preparation of this article is gratefully acknowledged. The examples presented in this article were contributed by members of other Metals Handbook welding committees. A total of 108 examples of gas tungsten-arc welding appear in other articles in this volume, as recorded in Table 12, on page 138.

of suitable size (Fig. 1a). As adequate fusion is achieved, a weld is made by gradually moving the electrode along the adjoining edges of the parts to be welded, so as progressively to fuse the parts together. Filler metal, when added manually, is often held at an angle of about 15° to the surface of the work and is slowly fed into the weld puddle (Fig. 1c). Filler metal must be fed carefully, to avoid disturbing the gas shield or touching the electrode, and thereby causing oxidation at the end of the filler rod or contamination of the electrode. The filler metal may be added continuously from a rod, or the rod may be dipped in and out.

Filler metal can be added continuously by holding the filler rod in line with the weld (as is often done in multiple-pass welding of V-joints), or by oscillating the rod and the torch from side to side, with the filler rod feeding into the weld puddle (a technique often used in surfacing).

To stop welding, first the filler metal is withdrawn from the puddle (Fig. 1d), but is momentarily kept under the gas shield to prevent oxidation of the filler metal; then the torch is moved to the leading edge of the puddle (Fig. 1e) before the arc is extinguished. The arc can be extinguished by raising the torch just enough to extinguish the arc, but not enough to cause contamination of the weld crater and the electrode. Preferred practice is to decrease the current gradually with a foot control without raising the torch.

Arc length equal to about 1½ times the electrode diameter is used in many applications of gas tungsten-arc welding, but it may vary for specific applications and, particularly, according to the welder's preference. The greater the arc length, the higher is the heat dissipation into the surrounding atmosphere. Also, long arcs ordinarily interfere, to an extent, with steady progression of the weld. One exception is the bell-and-spigot joint in piping or tubing welded with the pipe axis in the vertical position; here, a long arc will produce a fillet weld of smoother contour than will a short arc.

Manual and Automatic Operation. There is a distinction between manual and fully automatic gas tungsten-arc welding. Manual welding is done by a welder; fully automatic welding, by an operator. Refinements of manual welding such as foot controls for welding current and on-off switching are first steps toward automatic welding. The use of equipment that holds and drives the torch at constant or programed speed, that automatically adjusts arc voltage (arc length), and that has provision for automatic starting and stopping constitutes fully automatic welding (see section on Automatic Welding, page 134).

Table 1. Suitability of Types of Current for Gas Tungsten-Arc Welding of Various Metals

(E = Excellent; G = Good; NR = Not recommended)

Metal welded	Alternating current(a)	Direct current: Straight polarity	Direct current: Reverse polarity
Low-carbon steel:			
0.015 to 0.030 in.(a)	G(b)	E	NR
0.030 to 0.125 in.	NR	E	NR
High-carbon steel	G(b)	E	NR
Cast iron	G(b)	E	NR
Stainless steel	G(b)	E	NR
Heat-resisting alloys	G(b)	E	NR
Refractory metals	NR	E	NR
Aluminum alloys:			
Up to 0.025 in.	E	NR(c)	G
Over 0.025 in.	E	NR(c)	NR
Castings	E	NR(c)	NR
Beryllium	G(b)	E	NR
Copper and alloys:			
Brass	G(b)	E	NR
Deoxidized copper	NR	E	NR
Silicon bronze	NR	E	NR
Magnesium alloys:			
Up to ⅛ in.	E	NR(c)	G
Over 3/16 in.	E	NR(c)	NR
Castings	E	NR(c)	NR
Silver	G(b)	E	NR
Titanium alloys	NR	E	NR

(a) Stabilized. Do not use alternating current on tightly jigged assemblies. (b) Amperage should be about 25% higher than when straight-polarity direct current is used. (c) Unless work is mechanically or chemically cleaned in the areas to be welded.

Welder Skill. Selection and training of operating personnel depend greatly on the degree of automation used. Since gas tungsten-arc welding is most frequently used for joining sheet-metal parts in applications where one welder can readily manage the relatively light, small components to be welded, the welder often spends part of his time in cleaning, assembling, fixturing and tacking. Aside from the high degree of manual dexterity, patience and training required for producing quality welds, the welder sometimes must have the mechanical skills needed for properly assembling and fixturing the components to be welded.

The specific welding skills required vary from one process to another; for instance, a welder skilled in manual shielded metal-arc welding (stick electrode) will need additional training to qualify for gas tungsten-arc welding. In addition, special skills are involved in some applications, such as the placement and welding of consumable backing rings, and repair welding.

Inspection. The inspection of gas tungsten-arc welds can encompass the full range of nondestructive techniques — from surface inspection of sheet-metal weldments, to radiographic and ultrasonic techniques for heavier weldments in which subsurface defects are more likely to occur.

Welding Current

Current is one of the most important operating conditions to control in any welding operation, because it is related to the depth of penetration, welding speed, deposition rate, and quality of the weld.

Fundamentally, there are but three choices of welding current: (*a*) direct current, straight polarity (dcsp); (*b*) direct current, reverse polarity (dcrp); and (*c*) alternating current (ac). Certain desirable effects can be obtained by superimposing high-frequency current on all three. A guide to selection of the type of current for welding various metals is presented in Table 1.

Direct current, straight polarity (dcsp), is the type of current most widely used for gas tungsten-arc welding. It can produce satisfactory welds in almost all the common weldable metals and alloys.

In welding with dcsp, the electrode is negative and the work metal is positive, so that electrons flow from the electrode to the work metal. Because in all direct-current arcs 70% of the heat is generated at the positive, or anode, end of the arc, an electrode of a given size will support more straight-polarity than reverse-polarity current. Consequently, dcsp is the type of current to use if the hottest arc for a specific size of electrode is desired.

Straight-polarity direct current produces a deep, narrow weld bead, with penetration superior to that provided by the two other types of current. The narrow bead and deeper penetration, however, may cause difficulty when thin metal is welded with dcsp. Unlike dcrp or ac, dcsp will not remove surface oxides on aluminum, magnesium, or beryllium copper, but aluminum may be welded with dcsp by the use of specialized welding techniques, plus mechanical or chemical cleaning prior to welding (see Table 1).

More skill is required when using dcsp than when welding with high-frequency-stabilized alternating current, principally because of the normal absence of a high-frequency pilot discharge when starting the arc with dcsp. High-frequency current can be superimposed on dcsp by adding special apparatus to standard machines.

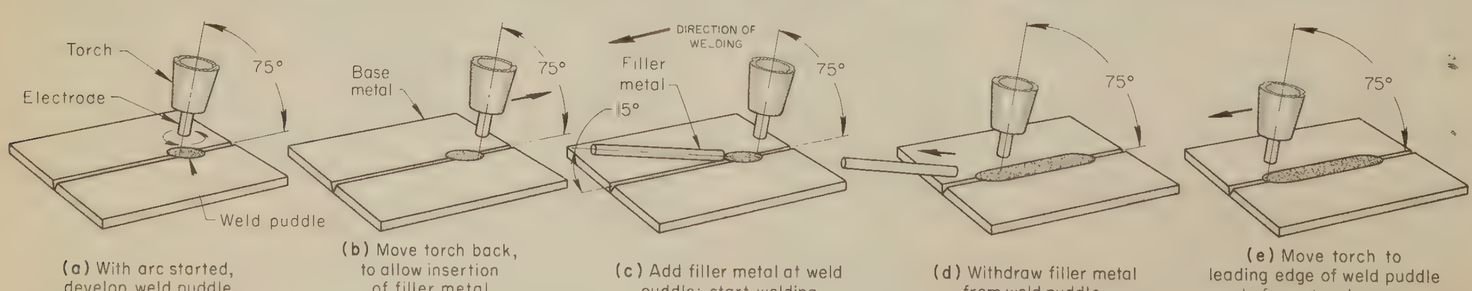


Fig. 1. Positions of the torch and filler metal in manual gas tungsten-arc welding. See text for discussion.

Direct Current, Reverse Polarity (dcrp). In welding with dcrp, the electrode is connected to the positive terminal of the power supply, and the work metal to the negative terminal. Thus, electrons flow from the work to the electrode, generating high heat in the electrode and low heat in the workpiece. At the same amperage and arc length, the arc voltage of a dcrp arc is somewhat higher than that of a dcsp arc, so that the dcrp arc has more total energy.

Reverse-polarity direct current is the least used of the three types of current, because it produces a flat, wide bead with shallow penetration. Welding with dcrp requires great skill and, because of the large size of electrode that must be used with a comparatively low level of welding current, is not generally recommended. Reverse-polarity direct current has the coldest *effective* arc of the three types of current, but it does provide superior removal of oxides from the surface of the work metal.

Aluminum is particularly difficult to weld with dcrp, because the weld puddle is readily attracted to the tip of the electrode, which becomes contaminated when touched by the aluminum. However, dcrp may be effectively used for joining thin aluminum sheet (up to about 0.025 in. thick). Magnesium, on the other hand, appears to be repelled by the arc action inherent to dcrp, and thus contamination is not a problem; dcrp may be used for welding magnesium in thicknesses up to ⅛ in.

Oxide Removal by Dcrp. Several theories have been advanced to explain the cleaning action whereby reverse-polarity direct current removes oxides from the surface of some base metals, but the generally accepted explanation is:

> When the electrode is positive, argon or helium ions travel to the surface of the base metal. Positively charged gas ions are produced through action of the arc on the surrounding inert-gas atmosphere. The gas ions have considerable mass and hence acquire large amounts of kinetic energy while speeding to the surface of the base metal. When these ions collide with the surface, they clean it by tearing away particles of oxide in a manner somewhat analogous to grit blasting. The ions produce little heating of the base metal, in comparison with the heating that occurs at the anode end of the arc; as a result, the amount of penetration is slight. If the electrode is negative and the work positive (straight polarity), the ions travel to the electrode and exert no cleaning action on the work metal, and electrons bombard the metal being welded, thus producing considerable heat and penetration of the work metal.

Metals such as stainless steel, carbon steel, and copper do not form oxide coatings that interfere appreciably with gas tungsten-arc welding.

Determining Polarity of the Welding Machine. In automatic gas tungsten-arc welding, there is little danger of starting the welding operation with the wrong polarity, because of the repetitive nature of the operation. In manual welding, however, polarity may accidentally be reversed through changing of the welding-machine leads, and it is well to test the polarity before starting to weld. This will avoid possible damage to the electrode, which would occur if a high reverse-polarity current were imposed on a small electrode.

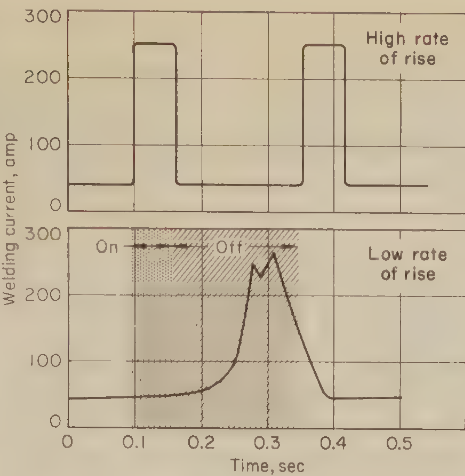


Fig. 2. Representative shapes of current pulses with high and low rates of rise

To test for polarity, a hookup for a metal-arc (stick) electrode holder can be incorporated in the circuit, and, using this holder, an arc is struck with a reverse-polarity, all-position, general-purpose shielded metal-arc welding electrode (class E6010). If the polarity is straight, the arc will have a strong, energetic hissing sound, not the energetic crackling sound of a true reverse-polarity E6010 arc.

Alternating current (ac) may be represented as a series of alternate pulses of dcsp and dcrp, and it reverses direction 120 times per second. With alternating current, the voltage varies from a maximum positive value to a maximum negative value during each cycle, and the arc is extinguished each time this occurs. A conventional arc welding transformer does not produce voltage high enough for positively re-establishing the arc after it has been extinguished when welding in an inert atmosphere; consequently, high-frequency current must be superimposed on the arc to re-establish the welding arc at each half cycle, unless the transformer used has a sufficiently high inherent voltage characteristic to render it unnecessary.

Alternating current gives good penetration and surface-oxide reduction, and the form of the gas tungsten-arc weld bead it produces when filler metal is added is more nearly that of a satisfactory shielded metal-arc deposit but with slightly less reinforcement. The bead produced in gas tungsten-arc welding with ac is wider and shallower than a dcsp bead, but narrower and deeper than a dcrp bead, and it has more reinforcement than either a dcsp or a dcrp bead. Alternating current is therefore preferred for the welding of aluminum, magnesium, and beryllium copper.

Prevention of Rectification in Alternating Current. Rectification, a phenomenon characterized by an unbalanced current sine wave caused by the unequal resistance to current flow during the positive and negative half-cycles of voltage across an alternating-current arc, may produce direct-current voltage components in the ac arc high enough to cause arc fluttering and instability. Rectification is more likely to occur in older transformers used for gas tungsten-arc welding; modern balanced-wave units are free of this.

Rectification occurs because the electrode and the weld metal emit unequal quantities of electrons. It is affected by the current density of the arc at the electrode and the workpiece, which controls the temperature of each. To some extent it is affected also by arc length and the shielding gas used. Rectification may produce dc voltage components as high as 12 volts. In the welding of aluminum, when the dc component is high the bright puddle of molten aluminum will darken and film over with oxide — the extent being proportional to the magnitude of the dc component.

Rectification, and its adverse effects, can be eliminated by the use of a balanced-wave transformer. This unit incorporates into the welding-current circuit a series capacitor (condenser) of a capacity that will permit the alternating welding current to flow efficiently but will block the direct-current component. These units are usually designed for open-circuit voltages in the range of 100 to 150 volts, require high-frequency current for arc starting only, and are used extensively in welding aluminum alloys and magnesium alloys.

Pulsed-Current Welding. Pulsed-current gas tungsten-arc welding employing a high rate of current rise and decay and a high pulse-repetition rate is widely used in the joining of precision parts. Pulsed current with slower rates of current rise and slower current-pulse rates is used in mechanized pipe welding and some other applications of mechanized welding.

Circuits have been developed that permit automatic precise control of the arc voltage of a pulsed-current tungsten arc. These circuits use the arc voltage produced by the high current pulse and lock the control during the remainder of the cycle. In sophisticated pulsed-current welding power supplies, the following may be set independently: pulse length at low current, pulse length at high current, amplitude of low-current pulse, amplitude of high-current pulse, and beginning of pulses. Figure 2 illustrates representative shapes of current pulses with high and low rates of rise, correlated with a scale of time in seconds.

The advantages of pulsed-current gas tungsten-arc welding are:

1. **Increased Depth-to-Width Ratios of Weld Beads.** By using a short-duration, high-current welding pulse with a small, blunt thoriated tungsten electrode, the arc force generated will produce weld beads in stainless steel that have depth-to-width ratios approaching two to one.
2. **Elimination of Drop-Through.** High-current, short-duration pulses will melt through root passes or thin work metal and solidify before the weld puddle becomes large enough to sag.
3. **Minimal Heat-Affected Zone.** The heat-affected zone can be minimized by proper proportioning of the high pulse height and pulse-on time and the low pulse height and pulse-on time. It is sometimes desirable to set the low pulse height at zero while holding a finite space between high-current pulses.
4. **Stirring in the Weld Puddle.** The high pulse of current develops arc and electromagnetic forces much greater than those developed with constant-

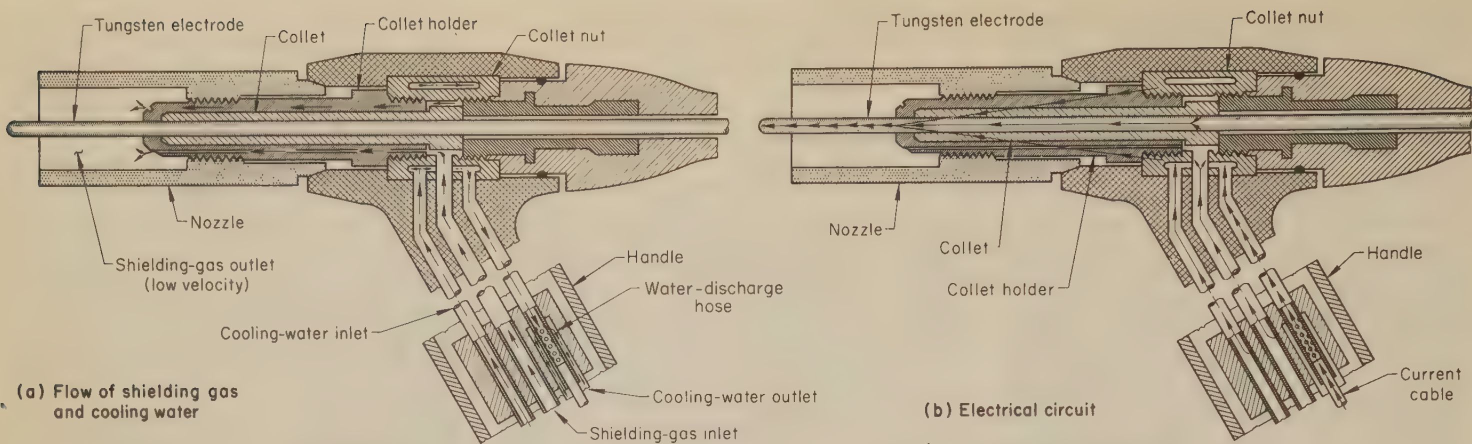


Fig. 3. Sectional views of a typical water-cooled torch for manual gas tungsten-arc welding

current welding. These high forces produce agitation of the weld puddle that reduces the porosity and incomplete fusion that may occur at the bottom of the joint. The pulsing also produces substantial arc stiffness when used for low-current welding, eliminating the arc wander associated with a low-current constant-current arc.

Power Supply

Power-supply units for gas tungsten-arc welding are: (*a*) transformer-rectifiers, for direct-current output; (*b*) transformers, for alternating-current output; and (*c*) power-driven generators — either electric-motor-driven (for dc output only) or engine-driven (for either ac or dc output).

Transformer and rectifier power supplies have several advantages over power-driven generators: low initial cost, no current dropoff during warmup, quiet operation, low maintenance and operating costs, no rotating parts, and low power input while idling.

The advantage of engine-driven generators is that they can be used in areas where electricity is unavailable.

High-Frequency (HF) Stabilization. Spark-gap or tube-type oscillators are incorporated into the circuitry of welding transformers for the purpose of starting the arc, and in some instances may be used continuously. In most early gas tungsten-arc welding done with high-frequency-stabilized alternating current, the radio interference that was generated created considerable difficulty. At present, however, vibrating relays, electron tube triggering circuits, and proper phasing of the high-frequency transformer furnishing a spark, supply a weaker discharge that interferes with radio reception to a lesser degree.

To adapt some older transformers equipped with HF-stabilized circuits to touch starting, they may be provided with a magnetic contactor in the ac power supply to be energized by a foot switch. With this setup, the welder can rest the electrode point at the desired starting location, drop his face shield, and then depress the foot switch. The arc starts when the electrode is raised from the work. This procedure is less tiring than others, and when the welder desires to stop the welding current he merely releases the foot switch.

The required intensity of HF pilot discharge depends on joint design, electrode extension, and the welder's ability to start the arc with the minimum of HF pilot-discharge current. If the weld is to be made in a deep groove joint, the HF-current intensity must be lower; otherwise, the arc will bridge the width of the groove rather than go to the root of the joint.

Excessive high-frequency stabilization may have the following undesirable effects:

1 Greater possibility of electric shock to operating personnel
2 Welding-arc instability
3 Crossfiring to metal nozzles (if they are being used)
4 Decreased life of the welding cable, because of high-frequency penetration of the insulation
5 Increased radio-reception interference.

When a high-frequency circuit is superimposed on the welding current, it is essential that the power be shut off before attempting to install or adjust electrodes, or before placing the hands on or near the metal parts of the welding head. Otherwise, a severe shock may result, particularly if the operator comes into contact with moisture that may be present near the work.

When welding with high-frequency-stabilized alternating current, a purple corona appears at the tip of the electrode while the electrode is hot after the arc is extinguished. As the electrode cools, the corona fades in intensity, and when the electrode reaches a certain temperature, the corona abruptly disappears. While the corona is visible, the arc will fire at a relatively great distance as the electrode approaches the work, and so great care must be taken to avoid accidental arc firing and arc burns at unwanted locations while the corona is visible.

"Hot Start" Devices. For certain welds it is desirable to furnish a surge of current substantially above the normal welding current, to initiate the weld with less time lag. This is particularly beneficial in automatic or semiautomatic welding. A "hot start" device incorporated into the circuitry provides this initial surge of current. Ordinarily, the device can be preadjusted to furnish the degree of additional current desired, and for the time span required.

Reduction of Power Surge. When welding at high current levels of short duration and with frequent starting, line surges can be reduced by connecting an induction motor across the line lead to the welding machine and running the motor without an external load. The horsepower rating of the motor should be in excess of the kilovolt-ampere rating of the welding machine, so that there will be enough kinetic energy in the rotating armature to return a substantial amount of power to the line when the line voltage drops because of the surge of current due to the short circuit set up in starting the arc. A sharp drop in line voltage will cause the motor to slow down, and rotational energy in the motor will be converted into electrical energy, which will help to hold the line voltage up. A careful cost study should be made before attempting an installation of this type, unless it is done on an emergency basis to reduce line-voltage drop at arc starting.

Reduction of Current for Crater Filling. In some applications, it is desirable to make a symmetrical closure of the end of the weld bead, and to avoid abrupt sagging or recession in the crater of the weld at the point of arc extinction. To do this in the welding of aluminum alloys and magnesium alloys, it is necessary to start reducing the welding current just before closure. However, some metals, such as some nickel-base and cobalt-base alloys, are so sensitive to thermal shock that crater cracks or "checks" invariably result unless the arc is extinguished with *gradual* reduction, assisted by the *over*-deposit of filler metal (which also quenches the heat from the weld puddle). The weld pass must continue beyond the end of the weld bead, and the current must be reduced to the point where the metal is no longer molten, in order to avoid a dimple or depression in the crater when the arc is extinguished. Otherwise, a trough or arc scar will be formed in the workpiece material when the arc is swung off. Such scars, and the microcracks that may be present in them, increase susceptibility to corrosion.

There are several methods of accomplishing gradual current reduction with the various welding machines: (*a*) by excitation control on motor-generators, (*b*) by variable-reactor control on rectifiers, and (*c*) by using a motor or an air cylinder to separate the primary and secondary coils on movable-coil or saturable reactors used to control transformers.

Welding Torches

A torch for manual gas tungsten-arc welding should be compact, lightweight, and fully insulated. It must provide a handle for holding it, a means for conveying the shielding gas to the arc area, and a collet, chuck or other means for securing the tungsten electrode and conducting welding current to it. The torch assembly normally includes various cables, hoses and adapters for connecting the torch to sources of power, gas and water (if water is used for cooling). A typical water-cooled manual torch is shown in Fig. 3. The shielding-gas passage through the entire system must be leakproof. Leaks in the hose or connections result in loss of valuable shielding gas and insufficient shielding at the weld puddle. Inspiration of air into the gas system is often a major problem. Careful maintenance is required to ensure a leakproof gas system.

Torches for gas tungsten-arc welding are available in a variety of sizes and types weighing from as little as three ounces to almost one pound. The different sizes of torches are rated in accordance with the maximum welding current that can be used. In addition, they will accommodate different sizes of electrodes and different types and sizes of nozzles. The head angle, or angle of the electrode with the handle, also varies on different torches. The most common angle is approximately 120°. However, torches with 90° head angles, straight-line (pencil-type) torches, and even adjustable-angle torches are available. Some torches have auxiliary switches and gas valves built into their handles.

The major distinction among torches for gas tungsten-arc welding is whether they are air cooled or water cooled. Air-cooled torches might more correctly be called gas-cooled torches, because much of the cooling is achieved by the flow of shielding gas; the only true air cooling is by radiation into the surrounding air. On the other hand, for water-cooled torches, some cooling is provided by flow of shielding gas, but it is supplemented by water that is circulated through the torch (Fig. 3a).

Air-cooled torches are usually lightweight, small, compact, and less expensive than water-cooled torches. However, they are generally limited to a maximum welding current of about 125 amp. They are normally used for welding thin metal and for limited duty cycles. The tungsten electrode operates at higher temperatures in air-cooled torches than in water-cooled torches, and this may cause tungsten particles to slough off into the weld puddle when pure tungsten electrodes are being used at or near current-carrying capacity.

Water-cooled torches are designed for continuous high-current welding. They will operate continuously with welding current up to 200 amp. Some are designed for a maximum welding current of 500 amp. They are heavier and more expensive than air-cooled torches.

The water hose and associated connectors are normally supplied with the torch. Generally, the power cable bringing the welding current from the power supply to the electrode is enclosed in the water-discharge hose (Fig. 3). This provides for cooling the cable and allows the use of a small-diameter, lightweight, flexible conductor. Adapter blocks, and sometimes flow switches and fuses, also are included. Water leaks in the torch or moisture contamination of the gas system will contaminate the weld and render the process inoperable.

Table 2. Typical Characteristics of Torches Used for Gas Tungsten-Arc Welding

Torch characteristic	Torch size: Small	Medium	Large
Maximum current usable (continuous duty), amp	100	200 to 300	500
Cooling method	Air(a)	Water	Water
Diameters of electrodes accommodated, in.	0.010 to 3/32	0.040 to 5/32	3/32 to 1/4
Nozzle-orifice diameters accommodated, in.	1/4, 5/16	1/4, 5/16, 3/8	3/8, 1/2, 3/4

(a) "Air-cooled" nozzles actually are cooled by the flow of shielding gas, and by radiation.

General characteristics of air-cooled and water-cooled torches are presented in Table 2.

Types of Nozzles. Several types of nozzles are used in gas tungsten-arc welding: ceramic, metal (cooled by radiation and the shielding gas, or water-cooled), fused quartz, and dual-shield nozzles. Ceramic nozzles cost the least and are the most popular, although water-cooled metal nozzles have longer service life, if properly used.

Ceramic nozzles become brittle after continued use and must be replaced when the lip of the nozzle becomes rough and uneven. A rough, uneven lip will interfere with the flow of shielding gas and cause nonuniform gas coverage of the weld area. Currently (1970), ceramic nozzles by one major manufacturer cost about 90¢ each in all orifice sizes (1/4-in. to 1/2-in. diameters). When welding with high-frequency current, ceramic nozzles must be used whenever possible, to prevent crossfiring to the gas nozzle (which often occurs when metal nozzles are used). However, crossfiring to the gas nozzle can be offset to a degree by using the largest-size nozzle that is practical for the application.

Sleeve-type, or slip-on, metal nozzles are very limited as to current-carrying capacity and, being delicate, are much more easily damaged and misused than the water-cooled types. Also, under the stress of continued use they run so hot that crossfiring destroys them immediately when it occurs.

Water cooling of metal nozzles makes it possible to use welding current as high as 500 amp, which is about the maximum practical for manual gas tungsten-arc welding (although automatic operations have used current well above 500 amp).

Fused-quartz nozzles are preferred by some welders, who maintain that superior vision of the weld operation is achieved by their use. Others, however, are dazzled by the brilliant light from the electrode, which is visible through the side of the nozzle up to the point where it emerges from the holding collet. Also, at the slightest contamination of the electrode, the violent ejection of metallic vapors away from its surface dulls the inside of the quartz nozzle, and visibility of the weld is thereafter severely impaired. In addition, even when the nozzle wall is clear, the vision aberration through it is so great that it is questionable that an advantage actually does exist.

Metal nozzles cooled by radiation and shielding gas ("air-cooled" nozzles) cost about $3.50 each; water-cooled metal nozzles cost about $12 each and range up to 3/4 in. in orifice diameter.

The substantial difference in cost between ceramic nozzles and water-cooled metal nozzles is sometimes offset by the rapidity with which ceramic nozzles are spent by welders who fail to give them reasonable care in the course of operation. Several ceramic nozzles may be used in a single shift by one welder if they are subjected to careless use.

The dual-shield nozzle permits a relatively small flow of argon or helium around the electrode to shelter the immediate weld puddle, while an annular grooved section around the central nozzle sends down an atmosphere of nitrogen or carbon dioxide to exclude air from contact with the central inert-gas column.

All gas nozzles, of whatever material, should be kept clean at all times, because an accumulation of foreign material on the inner surface — and, particularly, on the lip of the orifice — will eventually interfere with, or set up turbulence in, the gas column or may begin to pass vaporized metal down into the weld puddle.

Size of Nozzle. When choosing a ceramic nozzle for a specific job, an attempt should be made to use the smallest nozzle whose lip will not melt under the concentrated heat of the arc. A small nozzle will assist in maintaining a more stable and positive arc, permit welding in more restricted areas, and give better vision of the weld. Smaller nozzles provide some "compression effect" around the arc, which acts to make the arc more forceful, direct and concentrated. Larger nozzles, however, will give better atmosphere blankets at a slower gas-discharge rate than is provided by smaller nozzles. For metals such as titanium that are sensitive at elevated temperature to contamination from the ambient atmosphere, larger nozzles are safer.

Shape of Nozzle. The common form of gas nozzle is either cylindrical or tapered in the inner surface. Because commercially available nozzles are almost invariably round, however, does not necessarily mean that they are the most economical for all applications. Greater economy can ordinarily be achieved by using a nozzle designed for a specific production application.

Nozzles to which elongated trailing sections have been added have proved helpful for shielding welds made in metals with high susceptibility to gas contamination at elevated temperature. Nozzles have been made that have a section flared out or shaped in such a manner that the gas flow is altered to achieve a special effect, such as maintaining protection over the finished weld area for a longer period than will a conventionally shaped nozzle. This permits reducing the gas flow to the *welding* nozzle by a factor of two or three from the flow that would be required without a trailing shield, in order to achieve only a part of the protection offered by the special shield.

Although additional gas is directed into the trailing shield, the gas flows slowly and is ordinarily liberated through a porous metal baffle onto the heated metal surface that is to be protected. The purposes of the porous baffle are to avoid turbulence and to economize on gas. Some metals and alloys susceptible to gas contamination at elevated temperature could not be welded without such devices. The "trailing" nozzles should be of a form that will follow well behind the arc location itself (see Fig. 7 on page 380 in the article on Arc Welding of Titanium and Titanium Alloys).

Other nozzles have been designed so as to direct the gas flow *forward,* to offset a draft effect from the ambient atmosphere caused by a high speed of welding-head traverse over the work surface.

When it is necessary to weld in extremely restricted locations, special torches should be fabricated, if practical. When welds must be made where there is considerable interference, long, narrow nozzles are available or can be made. Round nozzles made from very thin copper brought down to a knife edge have been effective at exceptionally low gas flows.

Gas Lenses. Laminar flow has also been achieved by the introduction of a special screen inside the gas nozzle. This device, known as a "gas lens", permits projection of an uncontaminated column of inert gas to a considerable distance beyond the nozzle orifice.

Size of Gas Orifices in Torch Collets. In some older torches, many of which are still in wide use in industry, the gas orifices in the electrode-holding collet are so small that considerable turbulence is created in the gas column issuing from the torch nozzle. This distorts the coverage pattern of the gas over the weld. Enlarging the orifices by drilling and reaming overcomes this difficulty, and is worth considering should turbulence be encountered while an older torch is being used. When enlarging the orifices, it is important not to remove so much material that the collet will be weakened to the extent that it might fail structurally to hold the electrode securely.

Less turbulence and mixing with surrounding air will occur if the gas column issues from the nose of the gas nozzle with a minimum of deflection.

Electrode sizes (diameters) for torches with various sizes of nozzle-orifice diameters are typically as follows:

No. 4 (¼-in. orifice)	Electrode, 0.020 in.
No. 5 (5⁄16 in.)	0.040 in.
No. 6 (⅜ in.)	1⁄16 or 3⁄32 in.
No. 7 (7⁄16 in.)	⅛ in.

In general, a metal nozzle should have a slightly larger orifice than a ceramic nozzle for the same electrode size. When the diameter of a metal nozzle is too small, overheating occurs and the nozzle deteriorates rapidly.

Nozzles are attached to the torch by tapered friction fit or by internal or external screw threads. Electrodes are clamped inside the torch by collet or chuck, or by other means. Separate collets are required for each size of electrode. The various sizes of collets within the size range of the torch are made to hold the electrode securely by a threaded cap fitting. The electrode should be inserted in the collet so that the end extends beyond the end of the nozzle. The permissible amount of extension depends on the type of weld joint, the electrode size employed, and the type of torch used (see "Electrode Extension", on page 121). The collet assembly also carries the current from the torch body to the electrode.

The design of the cap on the torch governs the length of electrode that can be used. (No cap is shown on the torch in Fig. 3.) Cap extensions allow the use of electrodes as long as 7 in.

Centering of the electrode in the torch nozzle orifice is important, because a deflection will cause the arc to be offset from the center of the issuing stream of shielding gas. If the electrode is slightly bent, it may be straightened by pressing against it laterally after it has been heated and is red hot. Axial alignment of the electrode is easily checked by looking straight into the gas nozzle; it is unnecessary to apply a gage or similar device to attain precision in centering.

Collets are of either the split type or the draw type. Both types are effective in making positive electrode contact if properly adjusted. The bodies of most collets are made of a copper alloy, to obtain the efficiency of heat transfer and electrical conductivity offered by copper, although some collet bodies are made of 80-20 nickel-chromium alloy.

The inner surface of a collet should be smooth. Before a collet is placed in service, it should be thoroughly checked for burrs, which might decrease the efficiency of electrode contact. Poor contact contributes to poor current-carrying capacity.

The position of most electrode collets with relation to the end of the electrode is a compromise between being immediately adjacent to the heated end (which would be most efficient from the standpoint of heat withdrawal) or being withdrawn far into the gas nozzle (where it would offer least resistance to the flow of shielding gas, and thus would minimize turbulence in the issuing stream of inert gas).

Electrodes

The use of a nonconsumable electrode — that is, an electrode that does not supply filler metal — constitutes the major difference between gas tungsten-arc welding and other metal-arc welding processes.

Tungsten, which has the highest melting temperature of all metals (3410 C, or 6170 F), has proved to be the best material for nonconsumable electrodes. In addition to having an extremely high melting point, tungsten is a strong emitter of electrons, which stream across the arc path, ionize it and thus facilitate the maintenance of a stable arc.

Table 3. AWS Classifications and Composition Limits for Tungsten Arc Welding Electrodes (AWS A5.12-69)

AWS classification	Tungsten, % min(a)	Thoria, %	Zirconia, %	Other, % max(b)
EWP	99.5	...	...	0.5
EWTh-1	98.5	0.8-1.2	...	0.5
EWTh-2	97.5	1.7-2.2	...	0.5
EWTh-3(c)	98.95	0.35-0.55	...	0.5
EWZr	99.2	...	0.15-0.40	0.5

(a) By difference. (b) Total. (c) EWTh-3 is a tungsten electrode with an integral lateral segment throughout its length that contains 1.0 to 2.0% thoria; average thoria content of the electrode is as shown in this table.

Tungsten of commercial purity (99.5% W) and tungsten alloyed with either thoria or zirconia are the electrode materials used in virtually all applications of gas tungsten-arc welding. Pure tungsten electrodes cost about 25 to 35% less than the thoriated types, depending on finish.

Table 3 gives AWS classifications and compositions for tungsten and tungsten alloy electrodes.

Finish and Surface Condition. The two main types of finish with which tungsten arc welding electrodes are commercially available are a ground finish and a chemically cleaned finish. Electrodes with a chemically cleaned finish cost about 15 to 30% less than those with a ground finish, as shown by the following comparison of typical costs for pure tungsten and thoriated tungsten electrodes 1⁄16 in. in diameter by 2 in. long, with the two finishes:

Pure tungsten, ground	$0.50
Pure tungsten, chemically cleaned	0.42
Thoriated tungsten, ground	0.80
Thoriated tungsten, chemically cleaned	0.57

The arc is more stable when electrodes with a ground finish are used. The relative smoothness of the surface of a ground electrode has considerable effect at high current levels; the resistance offered by the rougher surface of a chemically cleaned electrode may reduce the maximum current-carrying capacity. Ground electrodes maintain maximum contact with torch collets. The smooth finish of a ground electrode ensures that a uniform surface is exposed to the arc, the gas stream, and the inner holding surface of the collet.

Electrodes made by drawing with the use of graphite as a lubricant may retain a slight coating of graphite and thus present a black or blue-black appearance. The graphite coating does not affect the arc or welding characteristics. Any other discoloration on the surface of a tungsten electrode, however, indicates the presence of tungsten oxide or some type of contamination. This will result in dirty welds and rapid consumption of the electrode, and may cause a wild and unstable arc.

If the electrode is discolored after use but has not been contaminated with filler metal or base metal, the discoloration is caused by oxidation. Ground or chemically cleaned electrodes will remain bright and shiny if properly protected from air contamination. The one exception is the graphite-drawn electrode, which will always be dark before and after use.

Electrodes having seams, cracks, pipes, slivers, or nonmetallic segregated inclusions should not be used. Any of these structural imperfections will substantially reduce the maximum current density that the electrode will tolerate. Also, irregularity on the surface of the electrode may cause the arc stream to "backfire" and attach itself to the electrode at some distance back from the tip; this results in a welding difficulty that need not have occurred.

Electrodes should be stored in a clean container until they are needed. Grease or dirt on the surface of tungsten electrodes will interfere with good electrical contact when they are inserted into the torch, and may cause damage to the torch through arcing to the collet. Also, dirty electrodes can contaminate the weld metal while welding is in progress.

Size. Standard commercial diameters and lengths of tungsten electrodes are given in Table 4. Table 5 lists typical ranges of current within which the various diameters of tungsten or tungsten alloy electrodes are used when welding with argon as the shielding gas.

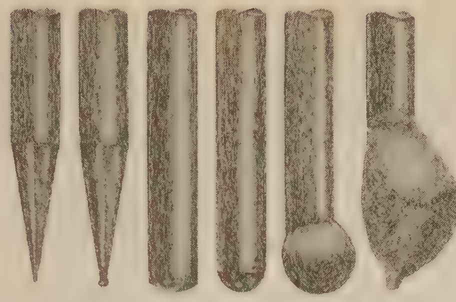
Generally the electrode size should be chosen so that the electrode will operate at near-maximum current-carrying capacity. At such a current level, the heat of the arc is more concentrated. This ensures maximum penetration, a stable arc, high welding speed, and minimum width and convexity of weld bead. The electrode size must be chosen for the current required and the speed desired for the specific application.

Authorities differ as to the electrode size that should be used for a specific current. Most agree that the smallest electrode that will maintain the arc without losing metal from the electrode tip in the form of molten drops or solid pieces should be selected for the unit current. Many users of pure tungsten electrodes grind a needle point on a much larger electrode than would ordinarily be used, and permit the electrode tip to "find" its normal current-density diameter upon the first striking of the arc. This practice, which is applicable *only* to pure tungsten electrodes, will automatically give an ideal electrode tip diameter.

The most stable arc for any particular electrode will be that which supports the maximum amperage without failing. Because of the high current-carrying capacity of tungsten electrodes and the large end-area differential existing between any electrode and the next larger or smaller size, it is not possible to attain an ideal current density merely by changing electrodes.

End Profile. Tungsten electrodes may have an end profile that is pointed, partly or completely hemispherical, or a bulbous mass of greater diameter than the electrode (see Fig. 4). A pointed end is ideal for welding in restricted locations, such as narrow joints in stainless steel piping, and it permits current density to be maintained at an extremely high level. An electrode with a hemispherical end profile will have the greatest current density, since less of the electrode end will be in contact with the arc. The thoriated and zirconiated tungsten electrodes will maintain their prepared end section over an extensive heat range, but pure tungsten electrodes will change their end profile according to the current density at which they are operating.

There is a method, previously mentioned, by which the end diameter of pure tungsten electrodes can automatically be adjusted to the specific job. In this method, after the heat required for the specific joint, metal, and welding position has been determined, an electrode is chosen that is in the general current range for the job. The electrode is then ground to a sharp point, with a taper three to six diameters long. When the pointed electrode is applied to the work, the point will melt back on itself until the tendency of the electrode mass to cool the molten tip balances the heat from the arc tending to melt it (see Fig. 4b). Thus, the molten section on the end of the electrode will have the ideal diameter for the specific job, and the diameter of this end section will rarely be identical with any available electrode size.



(a) (b) (c) (d) (e) (f)

(a) Thoriated tungsten electrode with pointed end, which will be maintained at a maximum current level for the entire electrode. (b) Pointed pure tungsten electrode that has attained ideal end diameter by method described in text. (c) Pure tungsten electrode with partly hemispherical end. (d) Pure tungsten electrode with fully hemispherical end. (e) Pure tungsten electrode with bulbous end. (f) Electrode contaminated with aluminum base metal or filler metal.

Fig. 4. End profiles of tungsten electrodes

Table 4. Standard Diameters and Lengths of Tungsten Arc Welding Electrodes (AWS A5.12-69)

Standard diameters, in.	Tolerance on diameter, in.	Standard lengths, all diameters(a), in.	Tolerance on length, in.
Diameters		Lengths	
0.010	±0.001	3, 6, 7	±1/16
0.020	±0.002	12, 18, 24 ...	±1/8
0.040, 1/16, 3/32, 1/8, 5/32, 3/16, 1/4	±0.003	(a) 0.010-in. electrodes also are available as coils.	

This method of preparing an electrode will add greatly to the ease of operation in executing any specific weld. It also avoids a difficulty that attends the use of a blunt-end electrode (particularly when welding in a deep groove) — that of the arc running up the side of the electrode. Several pure tungsten electrodes should be pointed before a job is begun. Then, if the electrode strikes the workpiece or the filler rod, it will be necessary only to change electrodes, instead of waiting for time-consuming regrinding of the point on the electrode being used.

When extremely thin and delicate sections are to be joined, it may be necessary to grind the smallest available electrode to a needle point in order to help stabilize the arc at extremely low current. If welding is to be done automatically, the grinding should be done by machine, so that the end profile is duplicated from electrode to electrode for repetitive use under closely controlled welding conditions.

Current-Carrying Capacity. Polarity, electrode holder, torch design, and the skill and ability of the welder all have great influence on the maximum current that an electrode will withstand. The surface finish of the workpiece also has some effect; the radiation from a mirrorlike workpiece surface will reduce the current-carrying capability of the electrode because of heat reflection, whereas a dull surface will permit the current to be increased. When the work metal has been preheated, the radiation of heat from the work will considerably reduce the current-carrying capacity of the electrode — although less current will be required for obtaining a given depth of penetration.

If the current range is too low for the electrode being used, the arc will wander over the end of the electrode. Excessive current values will cause the tip of a pure tungsten electrode to "ball up" and vibrate at high frequency, at which point the tungsten begins to transfer across the arc in the form of small particles and metallic vapor. Excessive current may also cause arc instability. When this occurs, there is a strong possibility that the large molten globule suspended from a pure tungsten electrode will drop into the weld puddle, contaminate it, and require mechanical removal before welding can proceed. Ideal arc conditions result when the molten tip of a pure tungsten electrode assumes the shape of a hemisphere. Stability of the arc will be promoted by using the smallest electrode at the maximum current value that will form the molten hemisphere at the tip.

Figure 5(a) shows the ends of pure tungsten electrodes after being used for welding at 300, 250 and 150 amp, with argon shielding. Note the erosion on the end of the electrode used at 150 amp, and the small projection on that electrode where the arc was concentrated but wandered over the surface of the electrode end. This wandering

Table 5. Typical Ranges of Current Used in Gas Tungsten-Arc Welding With Tungsten Electrodes of Various Diameters (AWS A5.12-69) (a)

Electrode diameter, in.	Direct current, amp: Straight polarity EWP, EWTh-1, EWTh-2, EWTh-3	Direct current, amp: Reverse polarity EWP, EWTh-1, EWTh-2, EWTh-3	Alternating current (high frequency), amp — Unbalanced wave: EWP	Unbalanced wave: EWTh-1, EWTh-2, EWZr	Unbalanced wave: EWTh-3	Balanced wave: EWP	Balanced wave: EWTh-1, EWTh-2, EWZr	Balanced wave: EWTh-3
0.010	Up to 15	(b)	Up to 15	Up to 15	(b)	Up to 15	Up to 15	(b)
0.020	5-20	(b)	5-15	5-20	(b)	10-20	5-20	10-20
0.040	15-80	(b)	10-60	15-80	10-80	20-30	20-60	20-60
1/16	70-150	10-20	50-100	70-150	50-150	30-80	60-120	30-120
3/32	150-250	15-30	100-160	140-235	100-235	60-130	100-180	60-180
1/8	250-400	25-40	150-210	225-325	150-325	100-180	160-250	100-250
5/32	400-500	40-55	200-275	300-400	200-400	160-240	200-320	160-320
3/16	500-750	55-80	250-350	400-500	250-500	190-300	290-390	190-390
1/4	750-1000	80-125	325-450	500-630	325-630	250-400	340-525	250-525

(a) Ranges are based on the use of argon as the shielding gas. Other current values may be employed, depending on the shielding gas (lower values would be used with helium as the shielding gas), type of equipment, and application. (b) These combinations are not commonly used.

sometimes leads to erratic following of the weld seam if mechanized welding is being used.

Figure 5(b) shows the ends of pure tungsten electrodes after being used for welding at 300, 250 and 150 amp, with helium shielding. The undercut appearance of the electrode used at 150 amp may result from both low amperage and low gas-flow rate.

Under extended periods of use in automated applications where only the molten hemisphere was permitted to form, no measurable usage of tungsten could be detected after 200 hr of continuous welding. When this form of electrode tip is presented to the work, not only is the current density the greatest, but also the arc gap may be the longest for any specific application.

Heating of the Electrode Tip. More heat is liberated on the positive side of a welding arc than on the negative side, because the impact of the electrons on the positive terminal heats it more than the negative. Consequently, when the polarity is reverse (electrode positive), the electrode becomes hotter than the workpiece, whereas with straight polarity (electrode negative), the workpiece becomes hotter. For example, to withstand the heat of a 125-amp current, a tungsten electrode must be ¼ in. in diameter if reverse polarity is used, but only $\frac{1}{16}$ in. in diameter with straight polarity.

Greater penetration into the work metal can be obtained using straight polarity, because about 70% of the heat of the arc is concentrated on the positive end of the arc stream, and only about 30% on the negative. Thus, straight-polarity current provides the most satisfactory heat transfer. However, when the arc is changed to reverse polarity, with the electrode positive, the current-carrying capacity of the electrode is reduced so much that continuous welding is maintained only with great manual skill and dexterity.

Excessive heating of an electrode can be avoided by changing to a larger electrode. Increasing the contact surface of the collet may also prove of some benefit. A non-water-cooled pure copper gas nozzle may be substituted for a ceramic nozzle; water-cooled nozzles will further assist.

The flow of inert gas has a certain cooling effect on the electrode, although if the welder attempts to use higher amperage by employing an abnormally high gas flow, the cost of doing so will be excessive.

Consumption of tungsten electrodes while welding is in progress is so small that it can be detected only by elaborate methods. A tungsten electrode loses material by inclusion into the weld metal, by condensation on the surface of the work, and by vaporization into the atmosphere.

The greatest consumption of electrodes results from striking the workpiece or the filler rod. Another cause of electrode consumption is improper shielding of the electrode after the arc has been extinguished. Also, the introduction of a contaminating atmosphere into the gas nozzle along with the inert gas causes tungsten oxide to be passed down from the oxidizing tungsten electrode.

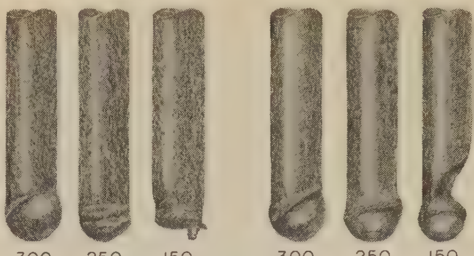


Fig. 5. Ends of pure tungsten electrodes after welding at three levels of current, with argon or helium shielding

If a tungsten electrode has been oxidized because the shielding gas was shut off too soon after welding was completed, when next the arc is restruck tungsten oxide will be thrown onto the work surface in the form of brilliant white particles, which pass through the arc with great speed. This throwdown, or "spitting", of tungsten oxide across the arc, coincidental with "missed cycles", may result also from instability of the welding transformer. To avoid tungsten spitting, it is necessary, after extinguishing the arc, to permit argon or helium to flow until the tungsten electrode becomes bright, silvery and shiny. Any discoloration on the surface of the electrode is caused by penetration of oxygen into the surface of the metal, and this oxidation may increase tungsten consumption by as much as twenty to thirty times.

If a large rate of consumption of electrodes is anticipated, it is best to use holders that will accommodate long electrodes, in order that the unusable electrode stub will be short in relation to the original length. For example, the unusable stub on a 3-in.-long electrode represents a much greater percentage of the original length than the stub on a 7-in. electrode.

Tungsten Contamination of Weld Puddle. When a pure tungsten electrode strikes the weld puddle, tungsten will be deposited in the weld metal. Because the contaminating tungsten may impair the strength and corrosion resistance of the welded joint, if the weldment is critical the welding operation should be stopped when such a strike has been made, and the tungsten should be mechanically routed out of the weld.

To remove the tungsten inclusions, carbide burrs must be used; an ordinary grinding wheel is likely to push the embedded particles even farther into the work as the wheel goes down into the material. For critical weldments, it may be necessary to radiograph the area to ascertain that all of the tungsten has been routed out before resuming welding. Tungsten particles show up as white flecks in weld radiographs.

Contamination of Tungsten Electrodes. During welding, the tip of a pure tungsten electrode reaches a temperature of at least 6200 F, which is above the melting point. Any filler metal or base metal that strikes the molten tip is vaporized to a degree. It also chills the molten tip enough so that the tungsten will combine with the filler or base metal to form an alloy. If welding is continued, the arc will be wild and unstable. When this occurs, there are two alternatives: (*a*) to break off the contaminated section of electrode and start welding with a clean section, or (*b*) to hold the arc on a section of copper or other material until the electrode has been cleared of contaminating metal through its vaporization. It can be seen through the filter lens that at the instant of clearing, the arc will stabilize itself and regain a normal welding condition.

The contamination of tungsten electrodes results not only in defacing of the workpiece, but also in loss of several minutes of welding time while the electrode is being cleared of the base metal plated on its surface or alloyed with it. When the electrode is being used at or near its maximum current capacity, if the torch is given a quick flip instantly after the electrode strikes the base metal or filler metal, most of the contaminating metal will slide down and off the end of the electrode. However, it may still be necessary to hold the arc for a short time on a piece of copper or other material, in order to clean the electrode completely. A considerable amount of electrode can be saved by this technique.

When welding stainless steel, if a pure tungsten electrode is contaminated with the base metal or filler metal, it is possible to maintain the welding arc without clearing the electrode, despite the wildness of the arc. This is not good practice, however, because contamination of the weld metal is almost certain to result. The arc instability results from the unusual shape of the contaminated electrode tip (see Fig. 6), and also from the passing of metallic vapors across the arc as the base metal or filler metal adhering to the electrode is vaporized. The electrode will not regain its proper form until the contaminated section is removed and readjusted to its proper extension beyond the nozzle orifice.

Once put into use and heated, a tungsten electrode is brittle a short distance back from the point. If the end of an electrode is to be removed, it should be gripped tightly with a pair of pliers and snapped off suddenly in the brittle area, generally within ⅜ in. from the end. If an attempt is made to break the electrode farther away from the point, the electrode will probably be bent rather than broken, thus causing subsequent difficulty in realigning it with the nozzle orifice.

Protection Against Oxidation. If electrodes are not protected by continued flow of the inert gas after the arc is extinguished, the usage of electrode may be up to 25 times as much as when protection against oxidation of the hot electrode is complete. However, it costs about six times as much for protective gas as it does for the wasted (or oxidized) tungsten. In addition, the cost of the welder's time must be considered.

The shielding gas may be shut off immediately upon completion of welding, without the necessity of permitting the tungsten to cool below oxidizing temperature, if the nose of the torch is introduced into a small ceramic crucible or metal hood at the moment the gas is shut off. The crucible will hold

enough argon to protect the tungsten while it is cooling.

If an electrode (other than one that has been graphite drawn) fails to attain a silvery color when the gas is permitted to flow until the electrode has cooled, there is air leakage into the gas system or the gas is impure.

Electrode Extension. Ordinarily, the distance an electrode extends beyond the orifice of the gas nozzle should equal the diameter of the electrode. The longer the electrode extension, the more danger there will be of striking the work metal or filler rod and contaminating the electrode. The farther the electrode tip is withdrawn into the gas nozzle, the less current the electrode will accommodate — probably because more arc heat is reflected back from the gas nozzle onto the electrode.

Ordinarily, the amount of electrode extension is dictated mainly by the profile of the joint to be welded. An inside fillet weld requires the greatest electrode extension, in order that the electrode may approach the root of the joint and yet permit some vision of the weld puddle. At the opposite extreme is an upstanding edge-flange weld, for which only a very slight extension is required, or no extension at all.

In some applications of welding with high-frequency-stabilized current, it is practical to withdraw the end of the electrode entirely within the nozzle nose. This has been done, for example, in welding an edge-flange joint between two 0.081-in.-thick sheets of aluminum alloy, wherein high-frequency-stabilized alternating current was used and the electrode was retracted 1/32 in. within the gas-nozzle nose. This practice makes it impossible for the electrode to become contaminated by touching the work surface. It does, however, interfere with weld visibility, and demands a high degree of welder skill. Also, when the electrode is retracted inside the gas nozzle and there is no possibility of contaminating atmosphere reaching the weld puddle, a black or gray material may appear in the center of the puddle if the arc is too long. This phenomenon has occurred while using unbalanced alternating-current transformers, and may have been caused by direct-current component passing across the arc.

For metals that require a very short welding arc, electrode extension should be greater than normal, to provide the welder with better vision and to assist control of the arc. However, the farther the electrode is extended, the greater must be the volume of gas flow to compensate for the greater distance of the gas nozzle from the workpiece surface.

As the inclination of the torch varies from one joint to another, some variation in electrode extension must accompany it. It is seldom necessary to extend the electrode farther than ½ in., although under special conditions of inert-atmosphere control, electrode extensions of as much as 3 in. have been used successfully.

In order to conserve gas and provide adequate shielding of the weld puddle, the electrode should be extended no farther than absolutely necessary. Also, any misalignment of the electrode axis within the gas nozzle will place the arc in improper relation to the shielding gas and may lead to insufficient coverage of the weld puddle. When welding with high current and a ceramic gas nozzle, if the electrode is slightly off center, the nozzle lip nearest the electrode may begin to melt and vaporize and thus contaminate the shielding gas.

Fig. 6. Typical shapes of pure tungsten electrodes, 1/16 in. in diameter, after contamination with stainless steel base metal or filler metal during welding

Thoriated tungsten electrodes contain up to 2.2% thoria (see Table 3). Unlike pure tungsten electrodes, thoriated tungsten electrodes do not melt at the usual current levels. For example, one ⅛-in.-diam thoriated tungsten electrode ground back ¾ in. from a needle point held a 450-amp dcsp arc for 12 min, at which time the grinding-wheel marks had disappeared from the surface of the ground portion only in the first 1/32 in. Failure of thoriated tungsten electrodes from excessive current is characterized by the sudden dropping off of a large length, rather than by the melting off of droplets as occurs with pure tungsten electrodes.

If high frequency is used in striking the arc, the arc will start instantly at lower current values than are required for touch starting. Also, the arc may be started at much greater arc lengths with complete arc stability, which is of prime importance when welding expensive materials that may have to be surface-finished to a high degree.

Touch starting with thoriated tungsten is free of the sputtering and flashing that may occur when pure tungsten is used. The best conditions for easy touch starting are high open-circuit voltage, thoriated tungsten electrodes, and argon shielding. The type of work metal also has a considerable influence on the comparative ease with which touch starting is accomplished; stainless steel is one of the easier alloys from this standpoint, whereas aluminum requires high open-circuit voltage for successful touch starting.

Climbing of the arc up the side of the electrode at reduced current values, which often occurs when pure tungsten electrodes are used, is not encountered with thoriated tungsten electrodes except after long periods of use.

The degree to which thoriated tungsten electrodes are superior to pure tungsten in current-carrying capacity when welding with alternating current may range from 0 to 50% (Table 5), and apparently depends on the amount of direct-current component and the amount of rectification in the arc. Current-carrying capacities of the larger thoriated tungsten electrodes are considerably higher with helium shielding than when pure argon is used. Compared with pure tungsten electrodes, thoriated tungsten electrodes provide somewhat greater arc stability.

The higher current density that can be tolerated by thoriated tungsten electrodes, and the ability of these electrodes to hold a point without melting, contribute to an extremely stable and "stiff" arc stream. The consumption of thoriated electrodes in manual welding is only 10 to 20% as great as that of pure tungsten electrodes, and in mechanized applications the advantage is many times greater.

At a given current level and arc length, less penetration is obtained when welding with thoriated than with pure tungsten electrodes, because arc voltage is from 3 to 5 volts less when thoriated electrodes are used. However, the much greater current-carrying capacity of thoriated tungsten electrodes more than compensates for the decreased arc voltage.

When a thoriated tungsten electrode is dipped into a molten puddle of stainless steel weld metal, ordinarily neither the weld metal nor the electrode will be contaminated, particularly if the welding is being done in the flat position. In the vertical, horizontal and overhead positions, however, a portion of the molten metal in the puddle often will adhere to the electrode and create a deformed outer profile. It is common practice to break off the section so contaminated, rather than to grind off the contaminating material, because of the difficulty of determining whether all the adhering material has been ground off before welding is resumed.

The pointing of thoriated tungsten electrodes is particularly beneficial for the welding of piping, or of joints with deep grooves. With a pointed electrode, there is extreme concentration of the arc force and the welding technique is assisted by the arc "stiffness".

It has been reported that there are certain low-current automatic welding applications for which pure tungsten electrodes are more satisfactory than the thoriated type. After a period of use, some thoriated tungsten electrodes permit the arc to attach itself to a part of the electrode other than the extreme tip. With continued use, the thoria inclusions may become segregated, and the arc may direct itself to these areas on the surface of the electrode, thus becoming unstable.

Zirconiated tungsten electrodes, which contain 0.15 to 0.40% zirconia (see Table 3), are well suited for applications in which contamination of the

weld with tungsten must be minimized. They retain a balled end during welding and are highly resistant to contamination; thus, they perform well when used with alternating current. Zirconiated tungsten electrodes are in common use, but are less widely used than thoriated tungsten electrodes. Both types are comparable in performance and applicability.

Effect of Tip Angle. In "The Effect of Electrode Geometry in Gas Tungsten-Arc Welding" (*Welding Journal*, Nov 1965, p 489s-496s), W. F. Savage, S. S. Strunck and Y. Ishikawa report that in gas tungsten-arc welding with straight-polarity direct current, the included angle at the conical tip of the tungsten electrode has a significant influence on (*a*) the voltage-current characteristics of the arc, (*b*) the penetration characteristics and the width of the weld puddle, and (*c*) the distribution of temperature along the length of the electrode.

For 2% thoria tungsten electrodes, centerless ground, the width of bead-on-plate welds decreased by a factor of nearly two when the vertex angle at the conical tip was increased from 30° to 120°. For the same increase in vertex angle, the depth of penetration increased by as much as 45%, while the cross-sectional area of the weld remained essentially unchanged.

From this investigation, it is evident that the vertex angle at the conical tip of a thoriated tungsten electrode should be specified and controlled if reproducible results are to be obtained with automatic gas tungsten-arc welding.

Shielding Gases

The main requirement of a shielding gas is that it exclude air from the weld puddle, the electrode, and the heated end of the filler rod (if used), to avoid contamination of the weld deposit. Shielding gas does not directly add heat to the weld. The gases ordinarily used in gas tungsten-arc welding are:

- Argon
- Helium
- Argon-helium mixtures
- Argon-hydrogen mixtures

The choice of shielding gas can significantly affect weld quality as well as welding speed. Argon, helium, and argon-helium mixtures will not react with tungsten or tungsten alloy electrodes and have no adverse effect on the quality of the weld metal.

Argon vs Helium. There is considerable difference of opinion about the relative merits of argon and helium for welding purposes. Each gas possesses characteristics that make it more suitable than the other for certain applications (see Tables 6 and 7).

Argon is more widely preferred, because it provides a "softer" arc, which is smooth and stable. Helium-shielded weld puddles are very hot and fluid, the weld metal is difficult to handle when pipe must be welded in the horizontal fixed position, and welding becomes more susceptible to manipulative errors. Argon is better for welding aluminum alloys, magnesium alloys, and beryllium copper; helium is less efficient in the surface-oxide cleaning characteristic that is essential when these metals are gas tungsten-arc welded. Greater penetration is achieved when using helium, and helium is used to good effect when fast, hot welding is desired for stainless steel.

Table 6. Characteristics and Comparative Performance of Argon and Helium as Shielding Gases

Argon

Low Arc Voltage. Results in less heat; thus, argon is used almost exclusively for manual welding of metals less than 1/16 in. thick.

Good Cleaning Action. Preferred for metals with refractory oxide skins, such as aluminum alloys, or ferrous alloys containing a high percentage of aluminum.

Easy Arc Starting. Particularly important in welding of thin metal.

Arc stability is greater than with helium.

Low Gas Volume. Being heavier than air, argon provides good coverage with low gas flows, and it is less affected by air drafts than helium.

Vertical and Overhead Welding. Sometimes preferred because of better weld-puddle control, but gives less coverage than helium.

Automatic Welding. May cause porosity and undercutting with welding speeds of more than 25 in. per min. Problem varies with different metals and thicknesses, and can be corrected by changing to helium or a mixture of argon and helium.

Thick Work Metal. For welding metal thicker than 3/16 in., a mixture of argon and helium may be beneficial.

Welding Dissimilar Metals. Argon is normally superior to helium.

Helium

High Arc Voltage. Results in a hotter arc, which is more favorable for welding thick metal (over 3/16 in.) and metals with high heat conductivity.

Small Heat-Affected Zone. With high heat input and greater speeds, the heat-affected zone can be kept narrow. This results in less distortion and often in higher mechanical properties.

High Gas Volume. Helium being lighter than air, gas flow is normally 1½ to 3 times greater than with argon. Being lighter, helium is more sensitive to small air drafts, but it gives better coverage for overhead welding, and often for vertical-position welding.

Automatic Welding. With welding speeds of more than 25 in. per min, welds with less porosity and undercutting mav be attained (depending on work metal and thickness).

Argon is used more extensively throughout industry than is helium. Argon is 1.4 times as heavy as air, but it will mix with air in confined spaces. Also, it is about ten times as heavy as helium and thus is better suited to welding in certain positions than helium, which rises rapidly from a weld after release from the torch nozzle.

Helium has only about one-seventh the weight of air and will mix with air only slowly. For welding of a given joint, a greater amount of helium than of argon must be used for shielding, because it is not feasible to confine helium to the weld area with dams and baffles, as must be done when welding gas-sensitive metals and alloys. The one exception is when welding is being done in the overhead position; then, baffles and dams can be used effectively to confine helium to the weld area and thus to achieve a beneficial shielding effect as well as to conserve gas.

Helium is ideal for welding in the overhead position, and for shielding the bottom side of joints welded in the flat position. In a vessel, helium will rise to the top. This constitutes a health hazard if the welder is working inside the vessel. In contrast, argon will sink to the bottom, and this must be considered if personnel are to enter and work near the bottom of a vessel.

Schlieren shadowgraphs show that the weight of the gas (whether argon or helium) has little effect on the immediate shield of the arc and weld puddle, and that adequate coverage is offered by either argon or helium. There is less entrainment of air into the issuing stream of helium than occurs with argon. Increasing the flow of argon after the necessary coverage has been established brings about an increase of turbulence without increased effectiveness of coverage. With helium, however, which induces almost no turbulence, additional coverage of area *is* attained by increasing the amount of flow. When welding aluminum with helium, a sootlike deposit forms adjacent to the weld. It has been determined that this deposit is condensed aluminum of submicron particle size. However, this deposit is not harmful, and it can be readily wiped away after the welding operation is completed.

Experimental work on thin sections of heat-resisting alloys has shown argon to be superior to helium for most applications of manual welding. The use of argon permits more latitude in joint fit-up, whereas a helium atmosphere requires a precisely fitted joint; otherwise, melt-through and irregular welds are certain to occur. It is customary to use argon for welding very thin sections because of the easily controllable arc argon provides and because minor variations in joint makeup and process adjustment assume greater relative importance in metals less than 0.062 in. thick when helium is used.

Manual welders may have difficulty in manipulating a helium-shielded tungsten arc because of the intensity of penetration and the greater heat liberated by this arc than by an argon-shielded tungsten arc. The use of helium requires considerably more skill than the use of argon, because argon permits a wide variation in arc length with a relatively small difference in heat input.

A helium-shielded arc emits about one-third more heat than an argon-shielded arc at the same current setting, because of the higher arc voltage of the helium arc. Some authorities state that about 10 to 20% more helium than argon is required for effective shielding of the weld puddle. However, 30 to 40% greater welding speed will be attained with helium because of the hotter and more intense arc it provides.

In one application of welding aluminum with argon shielding, gas consumption was 15 cu ft per hour, welding current was 350 amp, and welding speed was 16 in. per minute. When helium was substituted as the shielding gas, gas consumption was 19 cu ft per hour, but it was possible to reduce current to 250 amp and to increase welding speed to 26 in. per minute. Also, narrower weld beads with deeper penetration and higher reinforcement were attained than when argon was used.

With straight-polarity direct current, high-quality welds cannot be made in aluminum when argon shielding is used, but when high-purity helium is used, thoroughly acceptable weave beads and stringer beads can be made.

Argon-helium mixtures are used when the greater penetration of helium is desired but the arc-softening action of argon is helpful from the standpoint of control. A mixture of (by volume) 80 parts of helium and 20 parts of argon has been effective in such applications. If a hotter arc is desired when welding aluminum with argon, helium can be added until the desired penetration is obtained. Combinations of argon and helium are widely used for automatic welding, and are obtainable in various percentages in cylinders.

Argon provides greater coverage of the weld puddle at low flow rates, whereas helium gives maximum coverage at high flow rates. Experiments indicate that the 80-20 helium-argon mixture provides coverage almost midway between the two extremes.

Argon-hydrogen mixtures have been used for the welding of various metals with which the occurrence of porosity is a constant problem; Monel and silver are two examples. In one critical application of welding nuclear miniature tubing made of "A" Nickel, a mixture of argon with 2% hydrogen was used effectively when no other shielding gas or combination of gases could overcome the porosity problem encountered.

Mixtures of argon with 10 to 15% hydrogen have been used successfully for welding stainless steel. Argon-hydrogen mixtures should not be used for welding carbon or low-alloy steel.

When an argon-hydrogen mixture is used, the gas is caused to flow, then ignited and brought down on the work, continuing to burn during the welding operation. When hydrogen gas is used for any purpose, there is always the danger of encountering an explosive mixture unless precise procedures are used. Cases are on record in which considerable effort was expended by welders to manufacture fittings to permit the use of hydrogen for purposes for which it was not intended and serious explosions resulted. Although pure hydrogen will not explode (it will only burn), when combined with even a small percentage of air, hydrogen *will* explode.

The use of argon-hydrogen mixtures is probably less than 1/10 of 1% of total gas usage in welding. The purpose of argon-hydrogen mixtures is to increase arc heat as well as to offer some measure of control of weld-bead profile. Helium-hydrogen mixtures have been tried, with no significant advantage.

Oxygen-Bearing Argon Mixtures. Argon mixed with 1 to 5% oxygen is for use only with the gas metal-arc process, which uses a *consumable* electrode. If oxygen-bearing argon is used with the gas tungsten-arc process, the oxygen in the gas will cause very rapid deterioration of the electrode.

Nitrogen in a shielding-gas mixture is always detrimental to arc stability, because of the inherent steady attack on, and deterioration of, the electrodes. However, nitrogen markedly increases the voltage and attendant heat in the welding of copper and copper alloys, for which an extremely hot arc is essential.

If high-purity nitrogen is used as the shielding atmosphere for welding deoxidized copper, the higher arc voltage obtainable will permit higher current to be used with standard equipment. The efficiency of heat transfer is much higher than when argon or helium is used, and this will result in substantial economy. Nitrogen costs so much less than either argon or helium that its use would be favored for this reason alone. If thoriated tungsten electrodes are used, the electrode contamination by nitrogen will be so low as to be negligible.

Nitrogen is used in Britain for welding deoxidized copper, because of the shortage of argon and helium there; but this usage is unknown in the United States.

Argon-nitrogen mixtures are laboratory curiosities, with no practical use yet found for production welding.

Table 7. Suitability of Argon and Helium for Use as Shielding Gases in Gas Tungsten-Arc Welding of Various Metals

(Welding with direct current, straight polarity, unless noted otherwise)

Aluminum Alloys. Argon (with alternating current) preferred; offers arc stability and good cleaning action. Argon plus helium (with alternating current) gives less stable arc than argon, but good cleaning action, higher speed, and greater penetration. Helium (with dcsp) gives a stable arc and high welding speed on chemically clean material.

Aluminum Bronze. Argon reduces penetration of base metal in surfacing (for which aluminum bronze is used).

Brass. Argon provides stable arc, little fuming.

Cobalt-Base Alloys. Argon provides good arc stability, is easy to control.

Cupro-Nickels. Argon provides good arc stability, is easy to control. Used also in welding cupro-nickels to steel.

Deoxidized Copper. Helium preferred; gives high heat input to counteract thermal conductivity. A mixture of 75% helium and 25% argon provides a stable arc, gives lower heat input than helium alone, and is preferred for thin work metal (1/16 in. or less).

Inconel. Argon provides good arc stability, is easy to control. Helium is preferable for high-speed automatic welding.

Low-Carbon Steel. Argon preferred for manual welding; success depends on welder skill. Helium preferred for high-speed automatic welding; gives more penetration than argon.

Magnesium Alloys. Argon (with alternating current) preferred; offers arc stability and good cleaning action.

Maraging Steels. Argon provides good arc stability, is easy to control.

Molybdenum-0.5Ti Alloy. Purified argon or helium equally suitable; welding in chamber preferred, but not necessary if shielding is adequate. For good ductility of the weld, the nitrogen content of the welding atmosphere must be kept below 0.1%, and the oxygen content below 0.005%.

Monel. Argon provides good arc stability, is easy to control.

Nickel Alloys. Argon provides good arc stability, is easy to control. Helium is preferred for high-speed automatic welding.

PH Stainless Steels. Helium preferred; provides more uniform root penetration than argon. Argon and argon-helium mixtures also have been used successfully.

Silicon Bronze. Argon minimizes hot shortness in the base metal and weld deposit.

Silicon Steels. Argon provides good arc stability, is easy to control.

Stainless Steel. Helium preferred. Provides greater penetration than argon, with fair arc stability.

Titanium Alloys. Argon provides good arc stability, is easy to control. Helium is preferred for high-speed automatic welding.

Purity of Shielding Gases

Only welding-grade gases should be used in gas tungsten-arc welding. If commercial-grade gases are used, difficulties will occur.

For welding reactive metals such as titanium, tantalum and zirconium, which are penetrated at elevated temperature by detrimental gases present in the ambient atmosphere, gas of absolutely predictable purity must be used, in order to avoid difficulty during welding. Assurance that gas purity is being maintained can be obtained by periodically testing cylinders before use on production work. Relative coloration of the surfaces of welds made in inert-gas chambers has been used as a test criterion for purity.

The dew point of shielding gas should be −75 F or lower (11.4 ppm water vapor, by volume). Water vapor in impure helium dissociates in the arc and yields hydrogen and oxygen. The presence of hydrogen in the inert atmosphere causes porosity, and the oxygen forms a film over the weld puddle, which may impair the ease of welding and result in poor fusion, together with inclusions. The presence of nitrogen as a contaminant, in any concentration, will impair the speed of weld progression. Helium of less than 99.8% purity will contain excessive water. If welding is attempted with helium of such purity, difficulty may be encountered when the cylinder pressure drops below 50 psi. It may be necessary to discontinue use of the cylinder at this point unless the water is removed by use of a drying agent, such as magnesium perchlorate, in the venting system.

Cylinder Gas Contamination. To prevent contamination of inert-gas cylinders with other gases, an arrangement is generally entered into between the customer and the supplier, whereby the user is requested to leave a certain residual pressure in the cylinder at all times. This will assure the supplier that he will be freed of the necessity of purging any contaminating gases from the returned cylinder. The customer is permitted a price adjustment on the basis of the volumes of gas returned to the supplier. Usually, a residual pressure of 25 psi is sufficient to ensure against contamination of the cylinder prior to recharging.

Welding difficulty is often attributed to impurity of the shielding gas, but experience has shown that of all possible sources of trouble, the gas in the cylinder itself is least likely to be contributing to the difficulty.

Hoses and connections must be thoroughly checked against leakage, which can readily cause contamination of the inert atmosphere flowing to the torch. Every possible care should be taken to ensure that the pure gas from the cylinder is conveyed to the weld puddle through a system that is completely leakproof.

If commercial-grade argon or helium is used for welding, the residual gases in the cylinders will contaminate the weld puddle, resulting in weld porosity. Purity of gas must be considered for critical applications, although the purity of welding-grade argon and helium as now produced (99.995% purity) is generally satisfactory for almost all

applications. Passing the gas through a small chamber containing incandescent "getter" metals is one way of reducing impurities in inert gases to only a few parts per million.

Removal of Air From Argon. Figure 7 shows that four volume changes of argon in a 70-cu-ft atmosphere chamber can reduce air content to about 0.1% (which is adequate for welding most reactive metals), if the argon is introduced slowly (at 80 cu ft per hour), through a porous bronze or similar diffusing plate. If, on the other hand, the argon is introduced directly (without diffusion through a porous plate) at a *higher* flow rate (350 cu ft per hour, as shown in Fig. 7), and perfect mixing of the gases is assumed, a proportion of 0.1% air in argon will be reached after ten volume changes.

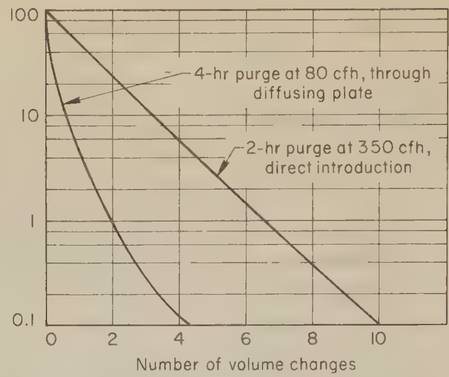


Fig. 7. Typical relation of purging times and gas-flow rates to number of volume changes required for removal of air from argon in a 70-cu-ft chamber

Gas Flow

Only enough shielding gas to exclude air from the weld location (and the heated area, for reactive metals and alloys) should be used. Excessive gas flow not only unnecessarily increases cost, but also may cause undercutting and arc instability.

The cost penalty for failure to give adequate consideration to economy of gas usage may be severe. In welding aluminum pipe, for example, gas-flow rates range from 25 to 45 cu ft per hour; at an approximate average cost of 10¢ per cubic foot for argon or helium in cylinders, the cost penalty for wasting gas is obvious. (The cost penalty is less with bulk gases; for example, bulk quantities of argon may be obtained for as little as 1.8¢ per cu ft.)

The minimum flow of gas required for maintaining adequate and effective coverage of the welding area is influenced by the following variables:

- Shielding gas used
- Distance of gas-nozzle orifice from the work surface
- Design of the weld joint
- Size of gas nozzle
- Shape of gas nozzle
- Size of weld puddle
- Amount of welding current
- Presence of drafts or wandering air currents
- Inclination of the torch
- Arc length
- Welding speed
- Position of the workpiece
- Metal or alloy being welded.

The list of variables above is in the general order of relative importance for most jobs, although specific applications may alter the relationship of these factors. In still atmospheres, effective shielding has been obtained with gas flows as low as 6 cu ft per hour for helium and 4 cu ft per hour for argon. These flow rates are only about half the rates normally used for average welding conditions, but they indicate the economy that is possible when all factors are under good control.

Shielding gas issues from the torch nozzle at relatively low velocity — about 10 ft per second — and thus the gas column is comparatively easy to disturb with drafts and air currents. The use of excessive gas flow to prevent the disturbance, however, not only is wasteful but also may be detrimental to the weld metal and the welding operation. Excessive flow also may cause an unstable arc at low welding-current values, and can result in undercutting of the work surface adjacent to the weld bead.

Only enough gas flow is required to exclude the surrounding air from the weld location; for argon, a flow rate of 8 to 12 cu ft per hour should usually be ample. If substantially greater flow than this is required to provide ample coverage, consideration should be given to the possibility of interference from drafts in the weld area, incorrect nozzle size for the specific job, or improper jig design.

Some flowmeters are calibrated in cubic feet per hour; others, in liters per minute. To facilitate correlation between gas flows, the conversion equivalents in Table 8 may be used.

Supply and Control of Shielding Gases

Shielding gases may be distributed from single cylinders containing gas or liquid, from portable or stationary manifold systems, or by pipelines that are connected to bulk storage tanks.

Supply. Single cylinders of gas or gas mixtures provide an adequate supply for operations consuming limited quantities. Single cylinders of liquid provide about three times as much gas as gas cylinders. Single cylinders have the advantage of maximum portability.

When the volume of gas required exceeds that which can be obtained from single cylinders, two or more cylinders may be joined together to form either a portable or a stationary manifold system. Portable manifold systems, of which there are two types, are extremely flexible and permit the manifolded cylinders to be located near the welding operation. In one type of portable manifold, the cylinders (usually from two to five) are connected by means of leads, called pigtails, to a common coupler block, from which they are connected to a single, common, pressure-reducing regulator. In the other type, which generally is used for more than five cylinders, the cylinders are joined successively by T's attached to the cylinder valves and by pigtails that successively join T to T. The gas from each cylinder passes through its T and flows into the main gas stream to a single regulator, which serves the entire group of cylinders. Both types of manifold systems can be assembled rapidly.

A stationary manifold system may be installed where large volumes of gas are regularly required or where a centralized gas supply is desired. This type of manifold consists of an adequately supported, stationary, high-pressure header to which a number of cylinders are connected with pigtails. One or more permanently mounted regulators serve to reduce and regulate the pressure of the gas flowing from the manifold into the piping system.

When stationary manifolds, truck trailers, or bulk supply systems are used as a source of gas, the gases are distributed by pipelines to the welding locations. The pipelines should be designed to handle and distribute the gases in sufficient volume and purity, and without undue pressure drop. Pipelines should incorporate all necessary safety devices (such as relief valves and bursting disks) to protect the system in case of mishap. Proper flushing procedures are necessary to achieve quickly the high purity available from distribution of liquefied gas. With the use of pipelines, an ample, uninterrupted supply of gas is available at all times.

Hoses and Fittings. It is essential to use plastic hoses for transporting helium, because at 20 psi, helium will diffuse through the walls of rubber or rubber-fabric hoses. The safer procedure is to standardize on plastic hoses for both helium and argon, to guard against possible gas diffusion. Vinyl chloride plastic, such as Tygon, has been used extensively for this purpose.

When setting up a gas tungsten-arc welding operation, it is best to use only new hoses and fittings, because old hoses may have been used for purposes that would have contaminated them. When old hoses are used for argon or helium, they may continue for a long time to contaminate the inert gas transmitted through them.

When argon or helium lines are disconnected, both male and female connections should be closed with pressure-sensitive tape or with plastic plugs, to prevent water or moisture, or other contaminants, from entering the gas passages. This is an important precaution; even the slightest deposit of water in the line will contaminate the inert atmosphere to the extent that the equipment cannot be used until considerable time and effort have been expended to remove the moisture.

Moisture contamination of the shielding atmosphere is indicated when the surface of the weld puddle loses its shiny, mirrorlike appearance (goes "cloudy") and visible masses of oxide or solid material float in the puddle. Also, the solidified weld metal will have a rough, irregular appearance. In the welding of aluminum, the slightest trace of moisture in an argon line causes the oxide to float on the surface of the weld puddle and a soft, sooty deposit to form around the puddle and along the sides of the weld deposit. Also, a brilliant indigo-blue color will appear outside the sooty deposit. This is caused by tungsten oxide thrown down on the material. Some welders

have been seen blowing into an argon line. This will cause condensation of moisture from the breath in the tube, and result in the difficulties mentioned earlier in this paragraph.

A systematic procedure should be used for installing or altering inert-gas systems to prevent damage to the work, loss of time, and unsafe practices. It is essential that all argon or helium connections be tight at all times; loose connections not only permit the loss and wasting of expensive inert gas, but also may draw air into the gas line and thus contaminate the atmosphere at the weld location, with consequent damage to the work. The tungsten electrode should be silvery in color on cooling; a bluish to green color denotes air leakage.

Regulators. A gas regulator is a mechanical device for reducing pressure automatically and controlling the volumetric flow of compressed gases. The four principal elements of a pressure-reducing regulator are:

1 A valve element consisting of a nozzle and a mating seat member
2 An adjusting screw, which controls the thrust of the bonnet spring
3 A bonnet spring, which transmits to a diaphragm the thrust created by the adjusting screw
4 A diaphragm connected with the mating seat member.

The bonnet spring holds the valve open until the gas pressure created on the underside of the diaphragm is equal to the thrust of the bonnet spring. The seat member then closes, or partly closes, against the nozzle, thus automatically throttling the flow of gas that is being withdrawn from the outlet of the regulator. A given set of conditions, such as constant inlet pressure, constant volumetric rate of flow, and constant outlet pressure, will produce a balanced condition whereby the nozzle and its mating seat member will remain in a fixed relationship to each other.

There are two basic types of pressure-reducing regulators: the stem type (sometimes referred to as inverse or negative type) and the nozzle type (sometimes referred to as direct-acting or positive type). These two types may be used in combination in a system as two-stage regulators.

Stem-Type Regulators. In the stem type of regulator, the inlet pressure acts to close the seat member against the nozzle. The outlet pressure of this type of regulator increases somewhat as the inlet pressure decreases. This increase is caused by a decrease in the force produced by the gas pressure against the seating area, as the inlet pressure decreases.

Nozzle-Type Regulators. In the nozzle type of regulator, the inlet pressure acts to move the seat member away from the nozzle. The outlet pressure of this type of regulator decreases somewhat as the inlet pressure decreases. The reason for this decrease of outlet pressure is that the force that moves the seat member away from the nozzle is reduced as the inlet pressure decreases. A smaller outlet pressure on the underside of the diaphragm is all that is necessary to close the seat member against the nozzle. The opening between the seat member and the nozzle is reduced, which results in less gas flow.

Two-stage regulators were developed to meet the need for more accurate regulation over a wide range of varying gas pressures. A two-stage regulator is a combination of two single-stage regulators in series, and it reacts as one unit.

Table 8. Conversion Equivalents of Gas Flow Rates

Liters per min	Liters per hr	Cu ft per hr	Life of 244-cu-ft cylinder, hr
1	60	2.1	116.2
2	120	4.2	58.1
3	180	6.4	38.1
4	240	8.5	28.7
5	300	10.6	23.0
6	360	12.7	19.2
7	420	14.8	16.5
8	480	16.9	14.4
9	540	19.1	12.8
10	600	21.2	11.5
11	660	23.3	10.5
12	720	25.4	9.6
13	780	27.5	8.9
14	840	29.7	8.2
15	900	31.8	7.7

The outlet pressure, from the first stage, is usually preset to deliver a specified inlet pressure to the second stage. By delivering a relatively low and very nearly constant inlet pressure to the second stage, an almost constant delivery pressure can be obtained from the outlet of the regulator, even though the supply pressure may vary.

There are several combinations of nozzle-type and stem-type regulators incorporated in one body that are used to make up a two-stage regulator. Regardless of the combinations, the increase or decrease in the outlet pressure is usually so slight (and apparent only at very low inlet supply pressures) that, for all practical purposes, the variation in delivery pressure is disregarded in welding operations.

Many kinds of regulators are produced for various applications. When single cylinders are used, the regulators need not have high capacities; a maximum of 1500 cu ft per hour is usually sufficient. When gas cylinders are manifolded, or a bulk system is used, regulators may have to accommodate a flow of 50,000 cu ft per hour, or more. Regulators at distribution-line stations are normally low-pressure types (up to 500-psig inlet pressure), and are available in various sizes depending on the volume demand at the particular station.

The outlet connections on gas cylinders are of different sizes and shapes to ensure against the possibility of connecting the wrong cylinder. Thus, regulators are made with different inlet conditions to fit the cylinders. The Compressed Gas Association has formulated a complete set of noninterchangeable cylinder-valve outlet connections. Regulator outlet fittings also differ in size and thread, depending on the gas and regulation capacity.

Flowmeters are used to control the flow of shielding gases. A flowmeter is equipped with a manual throttle valve for gas-flow adjustment. The flowmeter tube is calibrated for the specific gas being used, and the operator can set the rate of flow required. The flowmeter tube is calibrated at a positive pressure, which normally exceeds any back pressure produced by the apparatus and thus makes possible a time reading of the gas flow.

Regulator-flowmeter combinations step down the high pressure in the cylinder, or in manifolded cylinders, to a lower working pressure. This lower pressure is then received by the flowmeter. The required gas flow is controlled by the manual adjustment of a throttle valve. The flow is indicated on a flowmeter tube. In operations where the gas consumption is high, a central manifolded-cylinder system can be installed and the gas piped to the various welding stations. Manifold regulators maintain a constant delivery pressure in the piping system. At the welding location, a station flowmeter can be attached to the piping system.

Mixers. When a mixture of two or more gases is used, the mixture is made by metering the separate gases into a mixing chamber. Here the gases are combined and mixed, after which the mixture exits through a single port. Gas mixtures are also available in cylinders.

Maintenance of Adequate Shielding. Protection of the heated and welded surface is often not complete if the weld progresses too fast. To obtain satisfactory shielding at high welding speed, one or more of the special measures discussed here are required. Insufficient shielding may be corrected in some instances by inclining the torch in the direction of welding, by directing it backward over the finished weld, or by increasing the gas flow. Ordinarily, when reactive metals such as titanium and zirconium are being welded, special gas nozzles are used that direct the atmosphere back over the heated and welded surface (see the discussion under "Shape of Nozzle", on page 117 in this article). For these metals and alloys, which are subject to gaseous contamination in the solid state at elevated temperature, separate means of protection by inert atmosphere furnished from a separate source must often be provided. Sometimes even this is not wholly effective, and the entire operation may have to be done within an inert-atmosphere chamber. (See pages 375 to 382.)

Drafts and Air Currents. To avoid contamination of the shielding atmosphere brought to the weld area by the torch, the ideal location for gas tungsten-arc welding is a draftless area. If conditions of disturbed air exist, suitable baffle screens should be set up around the operation. If work is to be done in the open, a portable framework of convenient size may be erected around the work area. This may be covered by canvas, leaving an opening for entry. When welding with any gas-shielded process is done in the field, much time, effort and difficulty will be avoided by providing some method of proper protection against drafts.

Conditions of disturbed air can be overcome to a degree by delivery of a greater volume of inert gas to the work, but ordinarily this is inadvisable because of the much greater expense involved per unit weld, as well as the fluctuations in shielding obtained under such conditions. Inclining the torch toward the direction from which the draft is coming will help somewhat, but this will hinder the welding operation and make it more difficult to perform.

Accessory Equipment

Jigs or restraining fixtures should be used whenever possible, to hold workpieces in alignment and to exert pressure at the proper point so that the

work cannot move during heating and cooling. If alignment, or joint fit-up, is not maintained, expansion and contraction may cause distortion or mismatch of the welded joint. Principles of fixturing for gas tungsten-arc welding are generally the same as for other welding processes (see the sections on fixtures in the articles on Shielded Metal-Arc Welding, page 11, and Gas Metal-Arc Welding, page 90). However, fixturing is frequently more critical for gas tungsten-arc welding, because the workpieces are often made of thin metal and thus are more susceptible to deformation than heavy structural parts.

Tack welding may be used in manual welding operations in which the shape of the workpieces prevents the use of fixtures, or in which production quantity is too small to warrant the cost of fixtures. However, in semiautomatic or automatic welding, tack welds may impair control of arc voltage and of filler-wire feeding.

Weld backing improves the uniformity, appearance and contour of a weld. Thin work metal is usually backed to protect the underside of the weld from atmospheric contamination, which may result in weld porosity or poor surface appearance. Backing bars also absorb some of the heat generated by the arc and can lend support to the assembly and the weld puddle. A weld can also be backed up with inert gas, which serves to control penetration and maintain a bright, clean undersurface, but does not function as a support. Sometimes, metal backing bars and an inert gas are used in combination.

Nitrogen has been used effectively to back stainless steel welds, but caution is necessary to prevent contamination of the arc atmosphere with nitrogen, which will cause arc instability. The use of nitrogen for backing can contribute substantially to the economy of the operation.

In applications where the final weld composition must conform to extremely rigid specifications, particular care must be taken to exclude all atmospheric gases from the underside of the weld. This is accomplished by introducing an atmosphere of shielding gas into the relief groove of a backing bar (as shown in Fig. 8).

Automatic Welding. Fixtures for automatic gas tungsten-arc welding must be designed to permit rapid assembly of parts and easy removal of the weldment after completion. Where high-volume production welding is required, automated welding equipment in various combinations can be used. This equipment is composed of the machine head, control panel, and motorized carriages or work positioners that are employed to move the welding torch along the welding seam. The machine head contains the torch body and a wire-feed mechanism to supply the filler metal at a regulated speed. The control panel contains indicating meters for current and voltage; components that determine arc-starting time; time-delay relays for gas and water supplies; controls for current increase (upslope) or current decay (downslope); and controls for wire-feed starting, delay and stop. (See also the discussion under

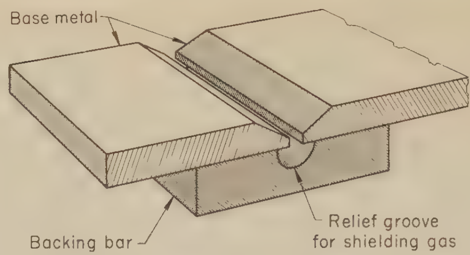


Fig. 8. Use of a backing bar with a relief groove for shielding gas, to exclude atmosphere from underside of weld

"Equipment" in the section on Automatic Welding, page 134.)

Longitudinal seamers, often called stake welding fixtures, are designed to locate and clamp both sides of a straight butt joint, as shown schematically in Fig. 9. The butt joint may be between two plates or be the longitudinal seam of a flat, conical, circular or rectangular workpiece. A longitudinal seamer consists of a base, which contains a weld backing bar to which the work is clamped by hold-down fingers, and an upper beam structure (not shown in Fig. 9), which supports a traveling carriage and track carrying the welding head, wire-feed mechanism, and clamping fingers. The upper beam structure is cantilevered, being secured to the base and hinged at one end for support, and with the opposite end remaining open to permit loading and unloading of the workpieces. A pivoted locking latch is provided at the loading end to restrain the cantilevered upper beam when the clamping force is applied.

The clamping mechanism is composed of two rows of hold-down fingers, which firmly hold the workpiece during welding. Each row may be independently actuated by means of manual or foot-operated valves that control mechanical, magnetic, hydraulic or pneumatic pressure systems. The intensity of clamping force may be controlled by means of a pressure-regulating device.

The backing bars are removable to permit the use of variously contoured groove openings for different thicknesses and types of metal. The bars may also contain relief grooves that permit flow of shielding gas to the underside of the weld (as in Fig. 9), and they may have provision for thermostatically controlled heating or cooling.

Pedestal boom manipulators can be used for rapid positioning and welding in any direction to produce internal or external longitudinal or circumferential (girth) welds. This equipment is suitable for use with power rolls or headstock-tailstock welding positioners on tanks, vessels, pipes and similar weldments. Rotating positioners, to which fixtures or other workholding tooling devices are mounted, are readily adapted to use with pedestal boom manipulators for small production runs or special fabrications.

Power supplies, filler-metal supplies, portable coolant tanks, automatic welding heads, and remote controls can be mounted on a pedestal boom manipulator. A typical pedestal boom manipulator that includes some of these features is shown in Fig. 10.

Pedestal boom manipulators can be moved manually, on integral wheeled bases, to work locations, or they can be powered to travel at welding speeds on rails.

Rotating positioners (see Fig. 16 in the article on Shielded Metal-Arc Welding) are probably the most adaptable type of fixtures for manual or automatic welding. The positioner worktable is a circular or square plate that has been machined to a flat surface and is fitted with T-slots for bolting down various jigs or workholding tools. The worktable can be rotated for 360° circumferential welds in any plane from flat to 10° past vertical. Variable rotational speeds and provision for smooth starting and stopping are mandatory for automatic welding operations. Pedestal boom manipulators are used to position the automatic welding head over the joint, and the positioner worktable may be started manually or sequenced to start automatically.

Skate welders are lightweight motorized travel carriages on which seam-tracking positioners, a wire-feed system and the automatic welding head are mounted. A skate welder enables precision welding of massive structures that cannot be handled by conventional rotating positioners and longitudinal seamers. Straight or curved track sections are attached directly to the workpiece by bolting or suction cups, permitting movement of the welding carriage in a continuous path along the weld seam. The skate carriage can be operated in horizontal and vertical directions to enable making out-of-position welds.

In skate welding of large assemblies, a mobile service carriage, which contains the power supply, the gas supply, all the control elements, and the operator, is synchronized to travel with the moving skate carriage during welding. Such equipment is satisfactory for long duty cycles on large assemblies.

Cables must be kept to a minimum length, and must be of ample size to handle the welding current. Excessively long cables or undersize cables will cause loss of current and voltage. Long cables should never be coiled up; rather, the proper length of cable should be obtained. Welding cables must not be operated at currents in excess of their rated capacity, or overheating and rapid deterioration of the insulation will result. Frayed or worn cables should be replaced or repaired immediately, to prevent short circuiting.

For welding with high-frequency arc stabilization, cables should be as short as practical, to prevent high-frequency attenuation. The cable between the high-frequency unit and the torch should be suspended from insulated hangers and not be taped or looped with other cables. In automatic welding operations where a jig or holder is used, all metallic parts containing the workpiece must be grounded, to prevent arc-over or burning.

Interfering radiation can escape in four distinct ways from an installation for machine welding by the gas tungsten-arc process in which high-frequency stabilization is used:

1 **Direct radiation from the welding machine.** This may be minimized if the

cover case of the welding machine is properly grounded.

2 **Direct feedback to the primary power line.** This may be prevented by enclosing the line in solid metallic conduit for at least 50 ft away from the welding machine in an unbroken line.

3 **Direct radiation from the welding cables.** High-frequency attenuation may be minimized by keeping the welding cable as short as possible.

4 **Pickup and reradiation from power lines and unshielded wiring.** Telephone wires, electric wires and ungrounded metallic objects up to 50 ft away from the welding machine may pick up high-frequency radiation and conduct it for some distance before reradiating a strong interference field in another area as a radiating antenna.

Water hoses should have a large diameter and be short, to minimize pressure drop in the flow of cooling water. Water flowing at about one quart per minute will provide adequate cooling of the torch. To maintain proper flow, a hose 12½ ft long must have a line pressure of at least 25 psi, and a hose 25 ft long should have a pressure of 35 psi. A pressure regulator may be required if supply pressure exceeds 35 psi; otherwise, the hoses may be damaged.

Cooling Water. Water-cooled torches must have a continuous supply of cool, clean water. In areas where the water supply has a high mineral content and contains excessive amounts of particles, it may be necessary to filter the water, to prevent clogging of the torch cooling passages. An alternative is the use of a water-recirculating system, as is required for portable equipment systems.

For portable installations, a water tank with a 10 to 40-gal capacity, equipped with an electrically driven pump, is usually adequate. The water tank should be filled with distilled, demineralized or deionized water. A bactericide or fungicide may also be added to further ensure its quality.

Equipment Location

Because welding cables, shielding-gas hoses, and water hoses must be short, the welding equipment and power supply must be near the work location. The following aids to equipment location have been used successfully:

1 **Portable carts** with integral water tanks, which will accommodate a power supply and gas-supply cylinders, and have racks for storing hoses and cables.

2 **Pedestal boom manipulators,** which have a tracked, car-type base that can be moved manually or by power. The base usually is large enough for one or more power supplies, gas-supply cylinders, and water tanks, and may be equipped with an operator's control station.

3 **Overhead track-type carts,** which may be equipped like the portable carts described above but with the primary electrical power supplied from a moveable slider contact on a bus bar. These units are difficult to maintain, but they provide a high degree of mobility for the welder and maximum utilization of floor space.

Filler Metals

The selection of a filler metal for gas tungsten-arc welding depends primarily on the base metal being joined.

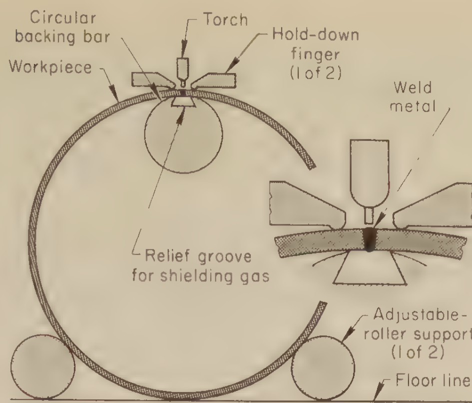


Fig. 9. Setup for automatic welding of longitudinal butt joints (see text)

Other influencing factors are: required mechanical and physical properties, joint design, and required finish or appearance of the welded part. To accommodate varied requirements, filler metals in a wide range of compositions are available for each group of alloys; Table 9 lists applicable AWS specifications. These specifications identify and give compositions for filler metals normally used for gas tungsten-arc welding; other compositions are available to meet more specialized requirements.

Forms, Sizes and Use. Filler metals are available in the form of rods, spooled wire, and consumable inserts.

For straight rods, standard diameters range from 0.030 to 0.25 in.; nominal length is 36 ± 0.375 in. Straight rods are available in 1, 5, 10, 25 and 100-lb packages. Wire diameters range from 0.020 to 3⁄16 in.; spools range in outside diameter from 4 to 12 in. Consumable inserts are designed to meet size and shape requirements of specific joints; some types of consumable inserts have been standardized.

Table 9. AWS Specifications on Filler Metals for Use in Gas Tungsten-Arc Welding of Various Metals

Metal welded	AWS specification on filler metals
Aluminum alloys	A5.10
Copper alloys	A5.7
Magnesium alloys	A5.19
Nickel alloys	A5.14
Steel, carbon	A5.18
Steel, stainless	A5.9
Titanium alloys	A5.16

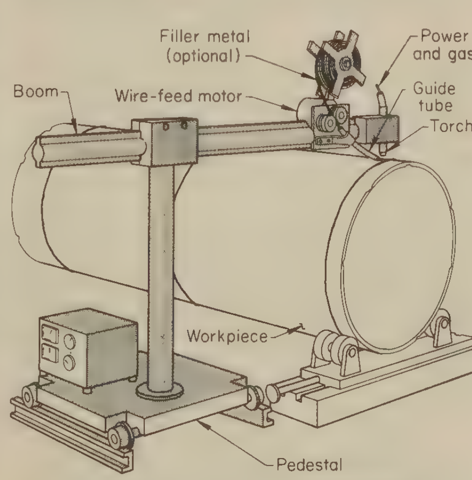


Fig. 10. Use of a pedestal boom manipulator for making a circumferential (girth) weld

Filler metals are added either manually or automatically during welding, or are added as preplaced consumable inserts. Manual additions are made by hand-feeding a filler rod to the weld puddle. Automatic feed systems supply filler metal, normally as spooled wire, to the weld puddle at a predetermined rate. Consumable inserts are placed in the weld zone before the arc is started, and are consumed in the weld puddle during welding (see also "Use of Consumable Inserts", page 128).

Storage and Preparation. Manufacturers of filler metals employ elaborate techniques to ensure that rod or wire is clean prior to packaging. Storage under improper conditions will very likely result in contamination of the filler metal. Any oil or other organic material on filler metal, or a heavy oxide film, will interfere with the deposition of sound weld metal.

Filler metal should be stored where condensation will not contaminate it. Normally, an area that has reasonably constant temperature and low humidity, and that is protected from oily shop atmospheres, is adequate. More elaborate facilities may include temperature and humidity controls or inert-gas chambers designed to remove air and moisture.

For most welding applications, filler metal that has been properly stored requires no specific preparation prior to welding. When necessary, straight rods may be degreased, cleaned chemically by etching, or rubbed with steel wool or abrasive to remove traces of oxide. These techniques may also be used to clean coiled filler metals, but uncoiling and recoiling is a time-consuming chore.

Joint Design

The five basic types of joints — butt, lap, corner, edge and T — are all used in gas tungsten-arc welding. Variations of these joints can be made to meet special requirements. Selection of the proper design for a particular application depends primarily on:

1 Mechanical properties desired
2 Cost of preparing the joint and making the weld
3 Type of metal being welded
4 Size and configuration of the components to be welded.

Edge and joint preparation are critical to the obtaining of sound welds, because proper joint fit-up is necessary — particularly for square-groove butt joints and any other joint to be made without adding filler metal.

Butt Joints. A square-groove butt joint is the easiest to prepare, and can be welded with or without filler metal, depending on the composition and thickness of the pieces being welded. A single-V-groove butt joint is used where complete penetration is required on work metal more than 3⁄16 to ⅜ in. thick. (The maximum thickness of square-groove butt joint that can be penetrated from one side depends greatly on composition of the metal being welded. For instance, the maximum practical thickness for stainless steel is approximately 3⁄16 in., whereas for an aluminum alloy this limit is about ⅜ in.) Filler metal must be used

for a V-groove weld. The included angle of the V-groove should be approximately 60°. The root face will be ⅛ to ¼ in. high, depending on the composition and thickness of the pieces being welded.

A double-V-groove butt joint is generally used on stock thicker than ½ in., when design of the weldment permits access to the back of the joint. Butt joints of special design are sometimes used for very thick work metal, which may require many welding passes (often by other processes in addition to gas tungsten-arc welding). However, the shape and dimensions of the portion of these joints where welding begins are usually close to those described above.

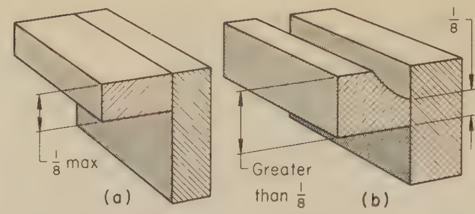
Butt joints of special design are used also in welding with consumable inserts (see Fig. 13 and the discussion under "Joint design" on this page).

Lap Joints. A lap joint has the advantage of eliminating the need for edge preparation. The only requirement for making a good lap weld is that the plates be in close contact along the entire length of the joint to be welded. This requirement is difficult to meet for thin base metal unless jigs and fixtures of appropriate design to provide adequate clamping are available. Otherwise, closely spaced tack welds may be necessary. Lap joints are difficult to repair, finish or clean, and they frequently have root defects.

Corner joints are used for fabricating boxlike structures. Two designs of corner joints are illustrated in Fig. 11. Assuming that the work metal is stainless steel, if the metal is no thicker than ⅛ in., the corners can be butted as shown in Fig. 11(a), and a satisfactory weld can be produced without filler metal; if the metal is thicker than ⅛ in., one of the corner members must be beveled or shaped as shown in Fig. 11(b).

Edge joints do not usually require the addition of filler metal. Three common types of edge joints are illustrated in Fig. 12; a feature common to all three types is that the thickness of the two components at the point of being joined is approximately the same. For joining thin turned-up edges, such as are illustrated in Fig. 12, some sort of backing for a heat sink is usually required to obtain uniformly fused edges.

T-joints require the addition of filler metal to provide the necessary buildup of fillet-weld size. The number of passes that must be made on each side of the joint depends on work-metal thickness and required weld size.



The thickness limits shown apply to stainless steel, or to metals with thermal conductivity similar to that of stainless steel.

Fig. 11. Corner joints for thin and thick metals

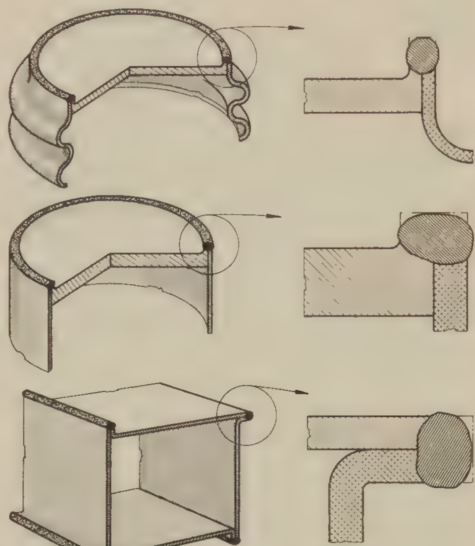
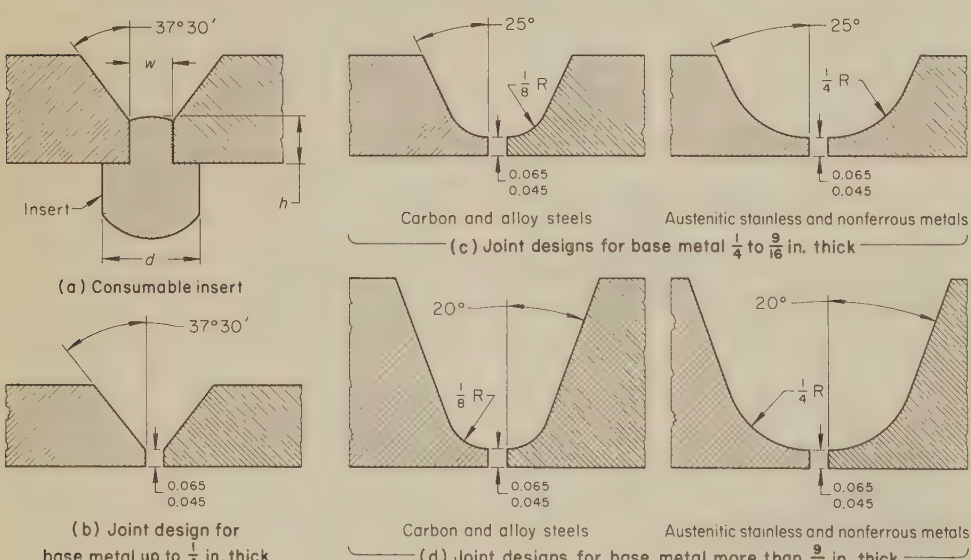


Fig. 12. Typical designs of edge joints



Nominal dimensions, *d*, *w* and *h* as shown in (a), for two sizes of inserts, are as follows: **⅛-in. inserts:** *d*, 0.125 in.; *w*, 0.047 in.; *h*, 0.055 in.; **5/32-in. inserts:** *d*, 0.156 in.; *w* and *h*, 0.063 in.

Fig. 13. (a) *Shape of one type of consumable insert placed between two pipe sections prior to welding.* (b), (c) and (d) *Joint designs for consumable inserts.*

Use of Consumable Inserts

The consumable-insert method of root-pass welding was originally developed for use in the fabrication of nuclear-powered submarines, for which the highest-quality joints are essential. This method is intended primarily for applications in which (*a*) accessibility is limited to one side of the joint; (*b*) smooth, uniform, crevice-free inner weld surface contours are essential; and (*c*) the highest quality attainable in the root pass is mandatory.

This method involves the use of an insert that is completely fused by a gas tungsten arc. The insert permits the deposition of a root-pass bead that is smooth and uniform even though welding is done from one side only. It provides full penetration to the root of the joint from the top side of the joint. The insert method is especially useful in butt welding of pipe, although there are no particular restrictions on its application. However, consumable inserts must be precisely fitted. Consumable inserts serve as backing rings, and are frequently specified in pipe welding.

Typical Insert. A cross-sectional view of one type of consumable insert is shown in Fig. 13(a); nominal dimensions of two common sizes of these inserts are noted below Fig. 13. Inserts of this type are available in a variety of compositions, including carbon, alloy, heat-resisting and stainless steels, and nickel and copper alloys.

The insert shown in Fig. 13(a) is placed between two pipe sections prior to welding. The inside diameters of the pipe sections at the root-face intersection may differ or be eccentric with misalignment of as much as 1/32 in. without any adverse effect on quality of joint or internal weld contour.

Joint design for use with consumable inserts of the type shown in Fig. 13(a) depends on the thickness and composition of the base metal, as illustrated in Fig. 13(b), (c) and (d). The single-V groove with shallow root faces (Fig. 13b) is satisfactory for base metal up to ¼ in. thick. For thicker metal, the design should be altered to U-grooves as shown in Fig. 13(c) and (d).

Welding Procedure. In most applications of joining with consumable inserts, gas tungsten-arc welding is used only for tacking and for the root pass. Other welding processes that are capable of depositing metal faster than gas tungsten-arc welding are ordinarily used for completing the weld. A typical procedure for using a consumable insert for making a high-quality weld that joins two pipe sections with the axis of the pipe in the horizontal-fixed position consists of the following:

1 Place an insert (ring form), with its overlap, on one pipe end that has been prepared (usually by machining).
2 Using a gas tungsten-arc torch, make small tack welds appropriately spaced to obtain a close fit, starting at one end of the insert and continuing halfway around the circumference.
3 Using a hacksaw or hand shears, cut off the overlapping ends so that the ends of the insert are butted together and the gap between the ends of the insert does not exceed 1/32 in.
4 Tack weld the remainder of the insert to the pipe end. One of the tack welds

should be at the splice where the insert ends are butted together.

5 Butt the second pipe against the insert that has been tacked to the first pipe end. The fit-up tolerance should not exceed $1/32$ in.

6 Midway between the original tacks, tack weld the second pipe to the insert and continue the tack across the insert to include the first pipe section.

7 From the top of the joint, weld upward first on one side, and then on the other, fusing the insert with the pipe ends to complete the root pass.

8 Complete the joint by any welding process, using filler metal.

For highest-integrity welds it may be necessary to use a backing of inert gas while welding the root pass. This is done by placing a cap over the end of the pipe and purging with an inert gas.

Although the procedure described above was developed primarily to produce high-integrity welds, it may also prove to be less costly than other methods, as in the following example of an improved joint design.

Example 128. Joint Redesign That Reduced Cost by Permitting a Root Pass To Be Made by Gas Tungsten-Arc Welding With a Consumable Insert (Fig. 14)

The longitudinal butt joints in 20-ft-long sections of SA-106, grade B, carbon steel pipe used for power-boiler headers were originally designed as shown at lower left in Fig. 14. With this design, the root pass and the second pass were made by shielded metal-arc welding using a backing bar, and then the weld was completed by the submerged-arc process.

To reduce cost, the joint design was changed to that shown at lower right in Fig. 14. This permitted making the root pass by gas tungsten-arc welding, using a consumable insert, instead of by shielded metal-arc welding with a backing bar. Then, as with the original joint design, the second pass was made by shielded metal-arc welding and the weld was completed by the submerged-arc process. The shielded metal-arc process was used for the second pass to provide a deposit thick enough to ensure against melt-through by the submerged-arc process.

Welding conditions for the improved joint design are given in the table that accompanies Fig. 14, together with a comparison of welding costs for both designs. As the comparison shows, the improved joint design and change in welding procedure resulted in a 25% saving in cost (material, labor and overhead) per foot of seam welded.

Cleaning the Work Metal

Welds made by the gas tungsten-arc process are extremely susceptible to contamination during the process. Therefore, the work metal must be free of grease, oil, paint, marking-pencil inscriptions, cutting lubricants, plating, dirt and oxides, or any other foreign material. It is possible, for instance, to pick up enough sulfur from soil contaminants to introduce brittleness in some joints. Heavily soiled workpieces (except those made of titanium alloys) are usually cleaned by immersion in emulsion or solvent cleaners followed by vapor degreasing with trichlorethylene. Phosphorus, lead, zinc, cadmium, and low-melting alloys, and iron contamination from metal stamping dies, also must be removed prior to welding.

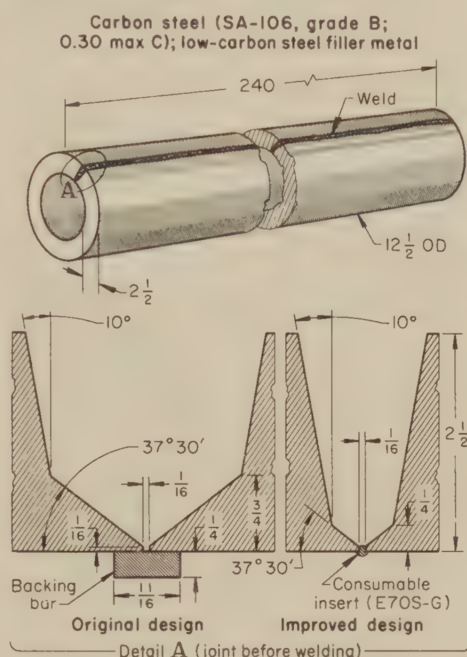
Simple degreasing is enough preparation for metals that have oxide-free surfaces. For metals with a light oxide coating, acid pickling treatments are generally used. Heavy oxide scales are removed by mechanical cleaning operations, such as grinding and abrasive blasting. When a plate having an oxide coating is sheared, the oxides may become embedded in the sheared edge. These oxides cannot be removed by chemical means, but must be removed by grinding or filing. Cleaning processes that should be used for various work metals are discussed briefly in the following paragraphs. (For more detailed information on cleaning of specific metals, see Volume 2 of this Handbook.)

Aluminum Alloys. Exposure to the atmosphere quickly causes the formation of a self-protective oxide coating on aluminum surfaces. This oxide coating, which is highly refractory and has considerable electrical resistance, must be removed by deoxidation with a hot alkaline cleaning solution, followed by rinsing in demineralized or deionized water.

Nickel alloys and stainless steel may be chemically cleaned by pickling to remove sand-blast residue or iron and other contaminants. The pickling solutions usually are composed of 5 to 20% nitric acid plus 0.5 to 2% hydrofluoric acid in water, and are used at 130 to 160 F; treatment time is 5 to 30 min, depending on the thickness of the contamination or oxide on the surface.

Carbon and low-alloy steels may be chemically cleaned in solutions of 50% hydrochloric acid in water; the acid treatment is followed by desmutting with an electrolytic chromic acid dip and by a cold-water rinse.

Titanium alloys may be descaled in molten salt baths or by abrasive blasting (see the article on Arc Welding of Titanium Alloys, which begins on page 375). Chlorinated solvents, such as trichlorethylene, should not be used for degreasing titanium alloys, because the chlorine residues cause intergranular attack in subsequent heating operations. Chemical cleaning may be performed by pickling for 1 to 20 min in solutions containing 20 to 47% nitric acid plus 2 to 4% hydrofluoric acid in water, or about a 10-to-1 ratio of nitric acid to hydrofluoric acid; bath temperature is 80 to 160 F.



Item	Original design(a)	Improved design(b)
Comparison of Costs per Foot Welded		
Weld metal	\$ 3.22	\$ 2.15
Labor and overhead	18.00	13.75
Total cost per foot	\$21.22	\$15.90
Saving with improved design		\$ 5.32

Welding Conditions for Improved Design

Welding process:
- Root pass .... Gas tungsten-arc
- Second pass .... Shielded metal-arc
- Remainder .... Submerged-arc

Power supply:
- Gas tungsten-arc and shielded metal-arc .. 200-amp transformer-rectifier(c)
- Submerged-arc .. 600-amp motor-generator(d)

Edge preparation .... Machined
Preheat .... 250 F min

Filler metal (mild steel):
- Gas tungsten-arc (argon shielding) ...... E70S-G, consumable insert
- Shielded metal-arc E7018
- Submerged-arc EL12

Power setting:
- Gas tungsten-arc ...... 90 amp, dcsp; 12 volts
- Shielded metal-arc .... 120 amp, dcrp; 23 volts
- Submerged-arc .... 450 amp, dcrp; 30 volts

Interpass temperature .... 500 F max
Postheat .... Stress relieve at 1150 ± 25 F(e)

(a) With the original joint design, the root and second passes were made by shielded metal-arc welding using a backing bar. Weld was then completed by submerged-arc welding. (b) With the improved joint design, the root pass was made by gas tungsten-arc welding using a consumable insert (no backing), the second pass by shielded metal-arc welding, and the remainder by submerged-arc welding. (c) With high-frequency start, and slope control. (d) Welding head on boom-type manipulator; workpiece supported on power and idler rolls for turning. (e) In furnace; 1 hr per inch of section.

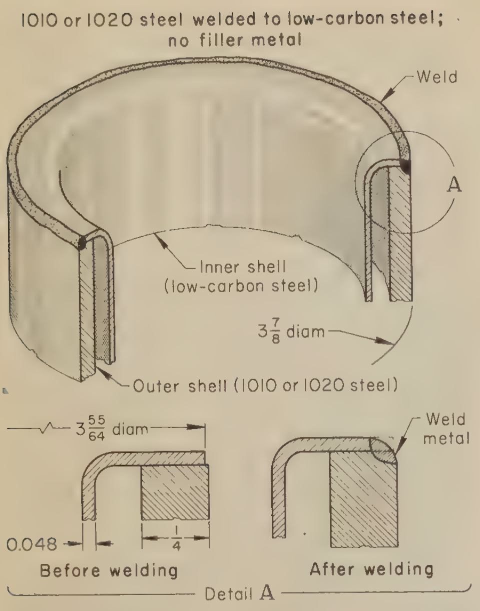
Fig. 14. Revision of joint design, entailing the use of a consumable insert, that permitted change to a lower-cost method of welding boiler-header pipes (Example 128)

Welding of Carbon and Alloy Steels

Carbon Steel. The weldability of carbon steel, for a given thickness and joint design, depends mainly on carbon content, and it is essentially the same for gas tungsten-arc welding as for other arc welding processes. As carbon content increases, difficulty in welding also increases — generally, in the form of cracking in the weld or in adjacent base metal. Thus, the requirements for preheating and postheating increase as carbon content increases, as in any other welding process. Other elements in carbon steel, however, such as sulfur, phosphorus and oxygen, generally have greater influence on weld quality in gas tungsten-arc welding than in other arc welding processes, such as shielded metal-arc or submerged-arc welding.

When gas tungsten-arc welding was first applied to carbon steels, the filler-metal compositions were selected on the basis of weld-deposit compositions obtained with the older, well-established processes. The result was that high-quality welds could not be produced consistently. Base-metal composition proved to be a major variable. For instance, rimmed steels were more susceptible to porosity in the weld than similar steels that were fully killed (see Example 139). Further, it was found that shielding gas, current density and other operating variables also had a marked influence on weld porosity in welding of carbon steel and must be kept under close control to obtain successful welds consistently.

For further information on welding carbon steels having higher carbon content (generally, more than 0.25% C), see page 187 in this volume.



Joint type	Corner
Weld type	Corner fillet
Process	Manual gas tungsten-arc
Electrode	$\frac{1}{16}$-in.-diam EWTh-2
Welding torch	250-amp, water cooled
Filler metal	None
Shielding gas	Argon, 8 to 10 cfh
Welding position	Horizontal or vertical
Current	120 amp, dcsp
Voltage	14 v
Arc starting and stabilization	High open-circuit voltage
Power supply	250-amp transformer-rectifier
Welding speed	25 to 30 ipm
Fixturing	Centering and hold-down clamps; variable-speed drive for rotation

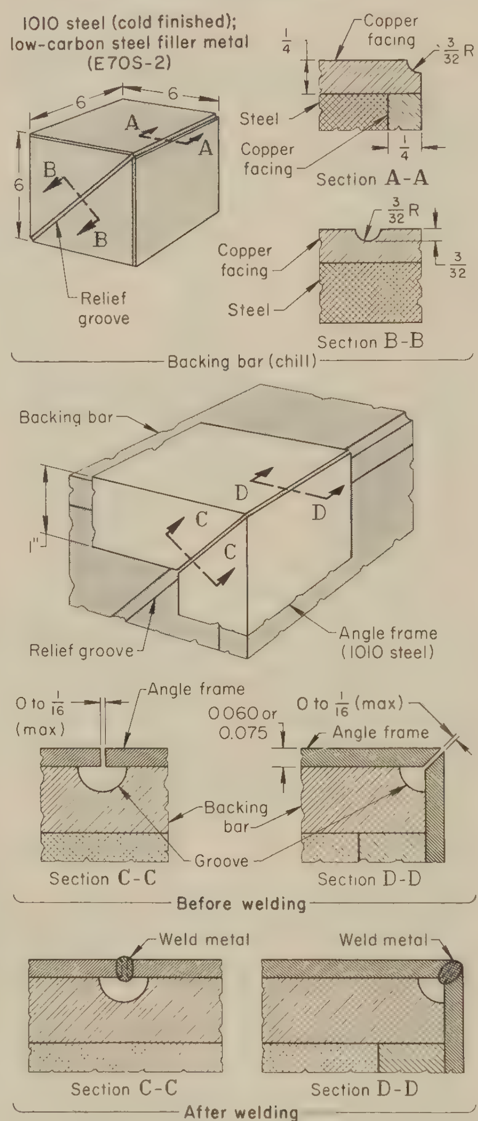
Fig. 15. Double-wall bearing mold welded by the gas tungsten-arc process at three to four times the speed obtained in gas welding (Example 129)

Alloy steels of all types are successfully welded by the gas tungsten-arc process. Alloy steels, however, particularly those that contain more than about 0.20% carbon, are far more susceptible to cracking than plain low-carbon steels. For this reason, all aspects of the welding practice must be under more careful control for alloy steels than is usually necessary for plain low-carbon steels. For instance, it is even more important that welds be located as far as possible from points of maximum stress. Joint design should be such that full penetration can be obtained and thorough inspection of the weld is possible. (For detailed information, see "Arc Welding of Alloy Steels", page 200.)

High-strength structural steels, also known as high-strength low-alloy steels, are welded by virtually all welding processes, including gas tungsten-arc. As with other alloy steels, susceptibility to cracking in the heat-affected zone is the most common problem in welding of these steels. However, some of these steels have specific properties or contain elements in amounts that intensify cracking difficulties during or after welding. For instance, some high-strength low-alloy steels contain relatively high percentages of phosphorus. Since phosphorus and sulfur increase susceptibility to cracking, it is desirable to keep the total content of phosphorus and sulfur well below 0.30%. Silicon contributes to cracking in some grades.

In welding these steels, inert gases with leading and trailing shields are often used to prevent weld contamination from the atmosphere. Preheating or postheating, or both, are often used to prevent cracking and to assist in attaining specified mechanical properties. In most applications, the use of gas tungsten-arc welding on these steels is restricted to the root pass; another process, such as shielded metal-arc or submerged-arc welding, is used for the remaining passes.

For further information on welding these steels, see the article that begins on page 200 in this volume.



Joint types	Butt, and mitered corner
Weld type	Square groove
Process	Manual gas tungsten-arc
Power supply	250-amp motor-generator
Electrode	$\frac{1}{16}$-in.-diam EWP
Arc length	$\frac{1}{8}$ in., approx
Filler metal	$\frac{1}{16}$-in. diam, same as E70S-2
Number of passes	One
Shielding gas	Argon, 20 cfh
Welding torch	150-amp, air cooled
Edge preparation	None (as-sheared)
Current	65 amp, dcsp
Voltage	Low-range setting
Welding position	Horizontal and vertical

Fig. 16. Use of a grooved backing bar in gas tungsten-arc welding of an angle frame, which reduced welding time and finishing time required when frame had been gas welded (Example 130)

Production Examples of Welding Low-Carbon Steel

Partly because of the difficulty in obtaining consistent results, and partly because gas tungsten-arc welding was generally considered a high-cost process compared with gas welding, shielded metal-arc welding or submerged-arc welding, there has been some hesitation in adapting the gas tungsten-arc process to the welding of low-carbon steels. However, consistent results can be obtained by close control of the steel being welded and the welding operation. Further, the cost of using gas tungsten-arc welding for carbon steels is not necessarily higher than the cost of competitive processes; in many applications, the finished weldment has cost less because production rate was higher, because control was better, or because the better appearance made possible by gas tungsten-arc welding eliminated, or at least reduced, post-weld operations. The four examples presented in this section describe specific applications for which gas tungsten-arc welding was used in preference to another process for one of the above reasons.

Gas Welding vs Gas Tungsten-Arc Welding. Although manual gas tungsten-arc welding differs greatly from gas (oxyacetylene) welding, the two processes are similar as regards manipulation. Both processes can be used with or without the addition of filler metal. (When filler metal is used, the welder has both hands occupied.) Although gas tungsten-arc welding allows less freedom of movement, filler metal can be added as needed, at the option of the welder. However, the tungsten arc produces a higher temperature, resulting in deeper, narrower welds made at higher welding speeds, generally with lower total heat input and narrower heat-affected zones. Both processes are used effectively on thin work metals. These similarities and differences suggest that manual gas tungsten-arc welding can be substituted for gas welding for higher productivity in selected applications, as described in the next three examples.

Example 129. Change From Gas Welding to Gas Tungsten-Arc Welding That Increased Productivity 300 to 400% (Fig. 15)

Double-wall steel cylinders of the design shown in Fig. 15 were used as molds for sleeve and journal bearings. The inner shell was a 0.048-in.-thick sleeve flared over at one end to a diameter $\frac{1}{64}$ in. less than the outside diameter of the outer shell. When properly centered, the sleeve could be slipped into the outer shell so that the flared edge could be welded to form a concentric annular closure (Fig. 15). The major welding problem was to obtain a leakproof weld without burning through the thin sleeve.

Gas welding, which was originally used for this application, produced satisfactory welds. For gas welding, the inner and outer shells were positioned in a plug-type fixture that centered the sleeve and permitted the flare to rest concentrically on the outer shell. With the assembly in the vertical position (Fig. 15), welding was done in the horizontal position. Because the flare edge was set back from the outside of the outer shell, a conventional fillet weld could have been used to make the joint, but it would have been too time-consuming. Instead, a slightly reducing flame was used to melt the

two edges of the joint, with the flame directed chiefly at the exposed corner of the outer shell. This technique not only avoided burning through the thin sleeve, but also provided the desired weld puddle. Filler metal — a high-tensile-strength (75,000 to 90,000 psi) steel rod of proprietary composition designed for fast deposition — was used only as required. Nevertheless, this procedure appeared to be too slow compared to the possibilities offered by manual gas tungsten-arc welding, and a change was therefore effected.

To take advantage of the higher welding speed of the gas tungsten-arc process, a new welding fixture was required. This fixture consisted of a centering device that clamped the shells in concentric alignment from the open end, and a spring-loaded clamp that held the flared end of the sleeve in positive contact with the outer shell. The unit was rotated by a variable-speed (0.10 rpm) drive actuated by a foot switch, and was additionally gimbal mounted to permit welding in either the vertical or the horizontal position.

Gas tungsten-arc welding was done in a single pass, entirely without filler metal. No change in the design of the shells was required, since the welding technique was essentially the same as that described for gas welding. To attain high speed with the new process, however, welders required special practice sessions. Welding speed was three to four times greater than that obtained in gas welding; the assemblies were gas tungsten-arc welded at the rate of 40 per hour. Additional conditions for gas tungsten-arc welding are given with Fig. 15.

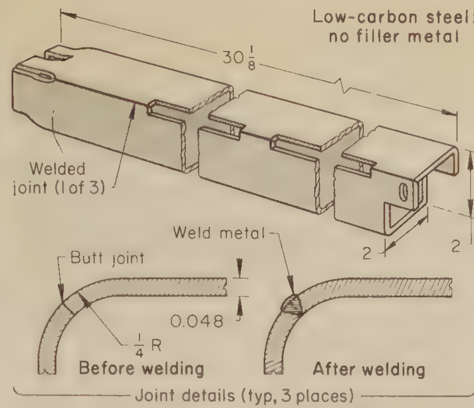
Examples 130 and 131. Change From Gas Welding to Gas Tungsten-Arc Welding, To Reduce Welding and Finishing Time

Example 130 — Angle Frames (Fig. 16). In the welding of butt joints and mitered corner joints in angle frames (see joint details in the lower views in Fig. 16), satisfactorily smooth appearance and freedom from distortion were more difficult to obtain than adequate strength. Formed from cold finished (rimmed) 1010 steel 0.060 or 0.075 in. thick, the angles varied from 1 by 1 in. to 1 by 3 in., and the welded frames varied from 3 by 3 ft to 4 by 8 ft over-all, with varying corner angles. Appearance was critical because the frames were assembled on the sides and ends of finished office equipment.

To minimize grinding and dressing, it was important to control weld buildup and heat input, as well as to avoid porosity and surface defects. Adhesive fillers could not be used to smooth surface imperfections, because they were not compatible with the phosphate coating and the high baking temperature of the enamel finish. Since the weld depended to some extent on the accuracy of forming and mitering, joint design called for a close-fitting square butt and corner joint with no overlap. Maximum permissible root opening was 1/16 in.

Originally, single-pass welds were made by manual gas welding. However, because of the weld-metal buildup, and the distortion and oxidation due to the heat input, considerable grinding and dressing were required. Changing to manual shielded metal-arc welding for six months resulted in only slight improvements, and a six-month trial using semiautomatic gas metal-arc welding with E70S-2 electrodes produced but a small improvement in finishing time. Then gas tungsten-arc welding was tried, and weld quality improved significantly.

Two particular requirements for gas tungsten-arc welding were: (*a*) the use of a backing bar, which served also as a chill; and (*b*) the selection of a filler metal designed to avoid porosity. The backing bar (see upper view in Fig. 16) consisted of a block of steel faced with 1/4-in.-thick copper shaped to fit the inside contour of the angle joints, with a groove 3/16 in. wide by 3/32 in. deep cut in the copper face to allow for underside weld reinforcement. The filler metal was of the same composition as the E70S-2



Joint type	Butt
Weld type	Square groove
Process	Gas tungsten-arc
Electrode	3/32-in.-diam EWTh-2
Welding torch	200-amp air-cooled copper cup with magnetic ring
Filler metal	None
Shielding gas	Argon, 30 cfh
Current	180 amp, dcsp
Voltage	16 v
Arc starting	High frequency
Power supply	300-amp motor-generator linked with high-frequency generator
Welding speed	75 ipm

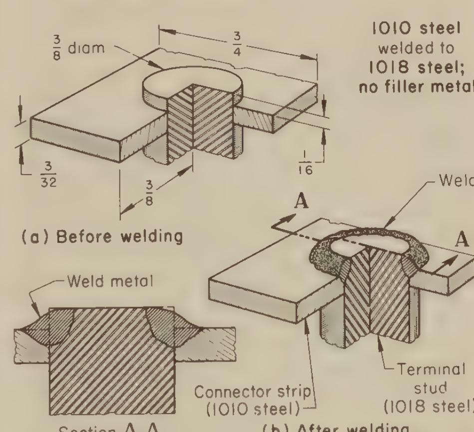
Fig. 17. Furniture leg for which welding time was reduced, and postweld cleaning eliminated, by change from gas welding to gas tungsten-arc welding (Example 131)

electrodes used in gas metal-arc welding. These are multiple deoxidized wires containing 0.40 to 0.70% silicon and a combined total of 0.20% zirconium, titanium and aluminum. Other welding details are summarized with Fig. 16. The benefits realized by gas tungsten-arc welding as compared with gas welding were as follows:

1. Grinding and finishing time were reduced by half.
2. Welding time was reduced 20%.
3. Porosity repair, which had run as high as 25%, was negligible.
4. Distortion and oxidation due to excessive heating were negligible.

Example 131 — Furniture Legs (Fig. 17). A furniture leg, consisting of a 2-in.-square tube 30⅛ in. long, was blanked and formed from cold rolled 0.048-in.-thick low-carbon steel, with a longitudinal seam that required welding in three places, as shown in Fig. 17. Good appearance was the major weld requirement. To keep costs down, a minimum of cleaning and finishing time was desired before painting. Originally, the welds were made by gas welding; the workpiece was clamped in a fixture, to form a close-fitting corner joint, and the edges were fused by means of an oxyacetylene torch without filler metal. Because the combined times for welding, and cleaning the welds for painting, appeared excessive, a change was made to gas tungsten-arc welding. No filler metal nor backing was used, no postweld cleaning was required, and welding time was greatly reduced.

For easy arc starting, a high-frequency generator circuit, timer controlled, was linked into the welding-current circuit of the motor-generator power supply. Another special feature of the equipment was an air-cooled torch, which was fitted with a copper alloy cup having a magnetic ring to prevent arc blow. Conditions for gas tungsten-arc welding are given in the table that accompanies Fig. 17.



Joint type	T
Weld type	Circumferential fillet
Process	Manual gas tungsten-arc
Electrode	0.060-in.-diam EWTh-2
Welding torch	150-amp, air cooled
Filler metal	None
Shielding gas	Argon, 10 cfh
Welding position	Horizontal
Fixtures	Locating jig and foot-operated turntable
Current	70 amp, dcsp
Voltage	10 to 12 v
Arc starting	High frequency
Arc length	0.06 in., approx
Power supply	200-amp transformer-rectifier (constant-current type)
Welding speed	4 to 6 ipm, approx

Fig. 18. Terminal stud gas tungsten-arc welded to a strip for connection to a helical resistor (Example 132)

Gas Tungsten-Arc vs Other Arc Welding Processes. In speed and cost, gas tungsten-arc welding is not competitive with other arc welding processes for most joining of carbon and low-alloy steels, provided acceptable results can be obtained by shielded metal-arc, gas metal-arc or submerged-arc welding. There are, however, some applications in which the degree of control afforded by gas tungsten-arc welding makes it the most efficient process. The example that follows describes an application in which shielded metal-arc welding was changed to gas tungsten-arc welding to obtain the desired results. (Two other applications, involving the welding of low-carbon steel to dissimilar metals, are described in Examples 134 and 135. In Example 135, the change to gas tungsten-arc welding also permitted a substantial cost saving.)

Example 132. Change From Shielded Metal-Arc to Gas Tungsten-Arc Welding for Better Control of Weld Deposit (Fig. 18)

Short lengths of cold rolled 1010 steel strip 3/32 in. thick formed the connections between the turns of a helical resistor and seven 3/8-in.-diam cold finished 1018 steel terminal studs of varying length. Because of the heat and stresses developed during operation of the resistor, the joint between connector strips and studs was welded (see Fig. 18), rather than being soldered or brazed. Originally, these assemblies were shielded metal-arc welded in a simple fixture. However, difficulty in maintaining control over the small weld deposit and the necessity for slag removal prompted a change to the gas tungsten-arc process.

The new method employed a special holding fixture mounted on a foot-operated turntable. Studs were inserted vertically through holes in a horizontal plate so that their lower ends rested on locating pins, which were adjustable to the several stud lengths. When properly located, each stud projected above the plate surface sufficiently to allow the connector strip to be placed over the stud leaving a 1/16-in. projection for a fillet weld (Fig. 18a).

Welding was done manually, without added filler metal. The arc was started at the center of the stud and moved to the edge, at which point the welder rotated the fixture by foot, while holding the torch 30° from vertical. After fusing the edge of

the stud to form a 1/16-in. fillet through one complete revolution, the arc was again brought to the center of the stud and extinguished.

Five of the seven studs required for each assembly were welded in this manner, under the conditions listed with Fig. 18. The two other studs, which were connected to the extreme ends of the resistor, had a joint design different from that shown in Fig. 18(b). For these studs, the connector strips were larger and were formed with a semicylindrical shape at one end, so that the stud nested in the shaped portion. These joints were also made with a 1/16-in. fillet weld, but a 0.040-in.-diam mild steel rod (E70S-3) was used as filler metal. One of these studs was welded on the special fixture described above; the other was welded manually without a fixture, after all other components had been assembled and welded.

Joining of the connector strips to the helical resistance coil is described in Example 134.

Welding of Stainless Steel

Gas tungsten-arc welding is used extensively for the various grades of stainless steel. It is used for welding of very thin sheet or strip, with or without the addition of filler metal, as well as for critical applications on material 1 in. or more in thickness. Welding equipment, gas shielding, tooling, and other processing conditions must be closely controlled for sound weldments. Filler metal compatible with the base metal must be used. For further details on the application of gas tungsten-arc welding to stainless steel, together with examples of production practice, see the article that begins on page 245 in this volume. (Table 12, in the present article, lists examples given elsewhere in this volume that deal with gas tungsten-arc welding of stainless steel.)

Welding of Heat-Resisting Alloys

Gas tungsten-arc welding is used for most grades of iron-base, nickel-base and cobalt-base heat-resisting alloys (Hastelloy D is an exception). Section thicknesses varying from thin sheet to about 1 in. are readily welded by manual or automatic methods. Direct current, straight polarity, is recommended for use when welding these alloys. Alternating current can be used for automatic welding where close control of arc length is possible. Appropriate selection of electrodes and filler-metal composition is especially important. Filler metal differing from base-metal composition may sometimes be used to control porosity or hot cracking. Close control of current, voltage, travel speed, shielding gas, and tooling is mandatory for producing sound welds. For further details on the application of gas tungsten-arc welding to heat-resisting alloys, together with examples of production practice, see the article that begins on page 277 in this volume. (Table 12, in the present article, lists examples given elsewhere in this volume that deal with gas tungsten-arc welding of heat-resisting alloys.)

Refractory Metals. Metallurgical characteristics of the refractory metals (molybdenum, tungsten, columbium and tantalum) preclude the use of any welding process that affords less protection to the hot metal than does the gas tungsten-arc process with the inert

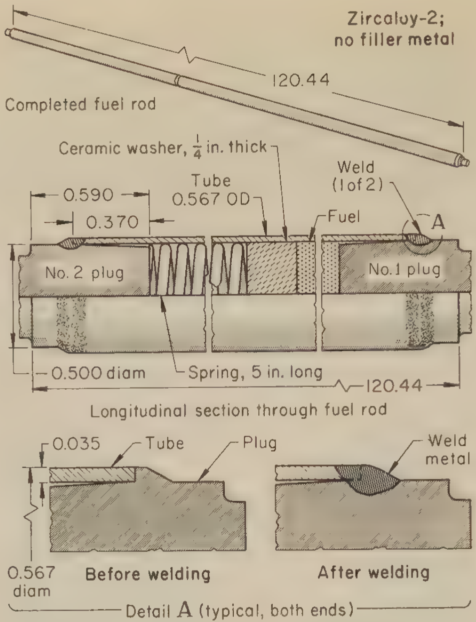


Fig. 19. Zircaloy-2 nuclear fuel-rod assembly joined by automatic gas tungsten-arc welding in a vacuum-purge chamber (Example 133)

gas shield. These metals must be protected from the oxidizing atmosphere. Under certain conditions it is possible to weld in the open with provisions for careful control by inert-gas shielding. Torch gas flow and backup shielding must be closely controlled. Usually, purged chambers containing high-purity inert gas are used. Close control of equipment and process, coupled with careful material handling for preparation and cleanness, is essential for welding the refractory metals.

Welding of Nonferrous Metals

Aluminum alloys, beryllium, copper alloys, magnesium alloys, nickel alloys, titanium alloys and zirconium alloys are all welded by the gas tungsten-arc process. The application of gas tungsten-arc welding to these alloys is discussed briefly in the paragraphs that follow. For more complete information and details of production practice, see the articles in this volume that deal individually with the welding of specific metals. (See also Table 12, in the present article, which lists examples given elsewhere in this volume that deal with gas tungsten-arc welding of nonferrous metals.)

Aluminum Alloys. Most gas tungsten-arc welding of aluminum alloys is accomplished with alternating current. Arc stability and length must be controlled. Control of the arc penetration and bead contour, to prevent any problems with undercutting, is also extremely important. Selection of the appropriate welding current and the correct electrode size for the specific joint is essential. Either argon or helium shielding gases may be used. Argon is generally used. Filler metal may or may not be used, depending on joint design and work-metal thickness. Good joint fit-up, cleanness of joint and filler metal, and close control of process variables are requisites for obtaining sound welds. Detailed information on welding of aluminum alloys is given in the article beginning on page 296 in this volume.

Beryllium can be welded by the gas tungsten-arc process. However, because of inherent characteristics of beryllium, the welds are brittle. Special precautions in handling beryllium are required because of its toxicity. Beryllium should be welded in a hooded enclosure, preferably a glove box. Techniques such as described for titanium alloys (see below) also are applicable to welding of beryllium.

Copper Alloys. Copper, copper-zinc alloys, copper-silicon alloys, copper-tin alloys, copper-aluminum alloys and copper-nickel alloys are all weldable by the gas tungsten-arc process. Each group of copper alloys requires special considerations.

Direct current, straight polarity, is normally used, but alternating current is satisfactory for some alloys. Both argon and helium shielding gas can be used, depending on the material to be welded. When welding material thicker than thin sheet, joints must have wide groove angles (60° to 90°), to permit proper manipulation of the torch and to obtain adequate penetration at the root of the joint. Root openings should be used to facilitate complete penetration. Detailed information is given in the article beginning on page 337.

Magnesium alloys are readily welded by the gas tungsten-arc method. Reverse-polarity direct current and alternating current are used to obtain different weld characteristics in various thicknesses of different alloys. (See the article beginning on page 358.)

Nickel alloys, as discussed in the preceding section "Welding of Heat-Resisting Alloys", are readily welded by the gas tungsten-arc process. (See also the article on Arc Welding of Nickel Alloys, beginning on page 366.)

Titanium Alloys. Titanium is highly reactive and in welding must be carefully shielded to prevent the absorption of oxygen, nitrogen, hydrogen or carbon. The absorption of these impurities will adversely affect mechanical properties of the weld and the base metal. In addition to the gas flow at the torch, shielding-cup leading and trailing gas shields are used. The trailing shield must provide protection for the weld area until the weld area cools below 1000 F. Leading shields should be used when the metal ahead of the weld is above 1000 F. Flow-purged chambers and vacuum-purged chambers are used to provide the most desirable inert-gas atmosphere. For quality welding, base metal and filler metal must be clean and shielding gas must be of high purity. Welding procedures must be specific for each individual setup.

Additional information on gas tungsten-arc welding of titanium alloys is given in the article on page 375.

Zirconium Alloys. The principal difficulty encountered in the welding of zirconium alloys is the contamination of the heated metal surface by oxygen and nitrogen. These impurities increase the hardness of the metal, and decrease the ductility and resistance to corrosion. Production of ductile, corrosion-resistant welds in zirconium alloys requires protection of the welded surface

by a rigidly controlled inert-gas atmosphere, often necessitating welding inside a chamber filled with inert gas. Zirconium alloys are also sensitive to traces of chemical contaminants, and to obtain high-quality welds, all joining areas must be carefully cleaned before welding.

Zircaloy-2 is commonly used for cladding fuel elements and end-closure joints of nuclear fuel rods. Welds for joining end plugs to tubing of fuel rods used in commercial (boiling water) nuclear reactors must be virtually defect-free, to avoid costly and often dangerous failure in service. In-plant specifications require close monitoring of all welding conditions and careful inspection of all welds. An automatic procedure developed for gas tungsten-arc welding in a vacuum-purge chamber is described in the next example.

Example 133. Joining Zircaloy-2 End Closures in Nuclear Fuel Rods by Automatic Gas Tungsten-Arc Welding (Fig. 19)

Figure 19 shows a nuclear fuel rod consisting of two end plugs and a tube, all of Zircaloy-2, which were joined by automatic gas tungsten-arc welding.

Equipment for welding included a cylindrical vacuum-purge welding chamber, about 15 ft long and 4 ft in diameter, specially designed to accommodate a batch of 100 fuel-rod assemblies, a rotatable chill-block fixture to clamp the tube in the horizontal position, and a 110-amp air-cooled torch rigidly mounted to hold the electrode in the vertical position for welding.

Before welding, a batch of tubes and end plugs was degreased, cleaned with detergent, dried, and loaded into the welding chamber. The tubes were placed in the horizontal position and handled by means of supporting trays. After being evacuated, the welding chamber was backfilled with a mixture of 92% helium and 8% argon; then each tube, manually fixtured, was inserted with a No. 1 end plug through glove ports in the chamber. The tube-and-plug assembly was rotated at a speed of 8 rpm for welding. Current at high frequency was used to start the arc, and the square-groove butt joint between the end plug and tubing (see Fig. 19) was welded in a single pass without added filler metal. Welding was done at 50 to 60 amp, dcsp, with no inert-gas flow at the torch; welding speed was 14.25 in. per minute. A 300-amp transformer-rectifier was the power supply; the welding electrodes were 1⁄16-in.-diam EWTh-2.

After welding of the No. 1 end plugs, each joint was subjected to visual, liquid-penetrant and radiographic inspection, and to corrosion tests. After inspection, acceptable tubes were loaded with uranium oxide pellets, a ceramic (Al_2O_3) washer ¼ in. thick, and a 5-in.-long spring. Then the tubes were assembled to No. 2 end plugs, fixtured, inserted through glove ports into the chamber, which had been evacuated and backfilled as before, and the No. 2 end plugs were welded to the tube, using the same procedure as for the No. 1 end plugs.

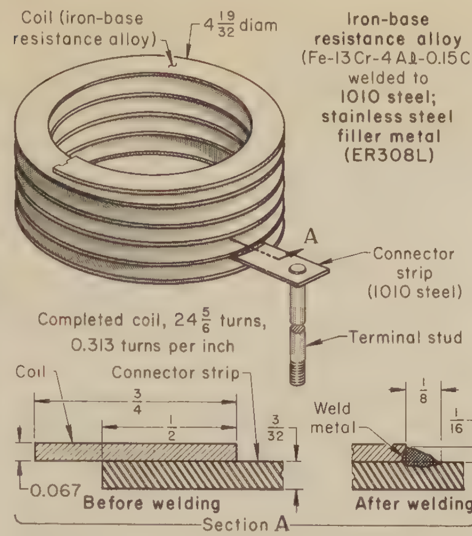
The completed fuel rods were subjected to a final leak test. Since helium had been sealed in the rods during final welding, a helium mass spectrometer was used for leak detection. The rods were loaded in a vacuum chamber equipped with a "snifter" probe. The chamber was evacuated, and a leak-rate measurement was taken. If a failure was detected, the rods were removed and tested in smaller lots until the defective rod was sorted.

Welding Dissimilar Metals

Various combinations of dissimilar metals are welded by the gas tungsten-arc process. Combinations commonly welded are carbon steel to stainless steel, and carbon steel to copper alloys.

Selection of filler metal generally is more critical for welding of dissimilar metals than for welding of similar metals (note Example 134). In welding steel to a copper-base alloy, the welding is started on the steel, which then serves to preheat the copper alloy (Example 135).

The two examples that follow describe applications in which shielded metal-arc welding was replaced by gas tungsten-arc welding, to obtain better control of weld deposit and less distortion in joining of dissimilar metals.



Joint type	Lap
Weld type	Single fillet
Process	Manual gas tungsten-arc
Electrode	0.060-in.-diam EWTh-2
Welding torch	150-amp, air cooled
Filler metal	0.045-in.-diam ER308L wire
Shielding gas	Argon, 10 cfh
Welding position	Horizontal
Fixtures	Coil-supporting jig with stud-locating template
Current	50 amp, dcsp
Voltage	10 to 12 v
Arc starting	High frequency
Power supply	200-amp transformer-rectifier

Fig. 20. Resistor assembly with detail of weld joining coil of iron-base resistance alloy and terminal connector strip (1 of 7) of low-carbon steel (Example 134)

Examples 134 and 135. Change From Shielded Metal-Arc to Gas Tungsten-Arc Welding

Example 134 — Better Control of Weld Deposit (Fig. 20). Resistor assemblies of the type shown in Fig. 20 required dependable joints between the resistance coil and seven terminal connector strips for stepped resistances. (Example 132 describes welding of these strips to terminal studs.) The coil consisted of 24⅚ turns of edge-wound flat wire 0.067 in. thick by ¾ in. wide, made of a 13Cr-4Al-0.15C iron-base alloy; connector strips were of cold rolled 1010 steel 3⁄32 in. thick by ¾ in. wide. Welding, rather than soldering or brazing, was used to make the joints, because of the heat and stresses developed in operation. At first, shielded metal-arc welding was used, but the procedure was changed to manual gas tungsten-arc welding because of difficulty in controlling the unequal-leg (1⁄16 by ⅛ in.) fillet weld (see Fig. 20).

Gas tungsten-arc welding was done with ER308L stainless steel filler metal, which was selected on the basis of laboratory tests to determine the most economical filler metal for the dissimilar-metal combination, and with the aid of a specially built fixture. This consisted of an L-shape bracket that permitted the coil to be held in the vertical position by a spring-loaded leather strap. The base of the bracket was drilled in seven locations to accept the stud end of respective connector strips. With the stud located in its proper hole, the end of the connector strip lapped under the edge of the resistor coil at the designated number of turns. The lap was then made snug by adjusting an elevating screw. To tighten the lap joint for welding, the two members were clamped by a vise-grip pliers modified with small tabs at the grips.

Welding was done by starting the arc approximately 1⁄16 in. from the edge of the strip, moving back to the edge and then carrying the puddle across the joint to the opposite edge. The torch was held at a 45° angle. After a momentary break in the arc, the weld was carried around the edge of the strip to prevent cracking at this point. This procedure was followed in sequence for the seven joints. Other welding conditions are given in the table with Fig. 20.

Example 135 — Improved Results, Lower Cost (Fig. 21). The boxlike weldment shown in Fig. 21 consisted of two naval brass bars to which were welded side plates of 1018 or 1020 steel. Used as a sliding ram, the assembly was installed in the front end of a lift truck to push the load forward off the truck. Tolerances on width and height (see Fig. 21) were important, because the assembly was not machined after welding.

Originally, the four corner joints were continuously fillet welded using shielded metal-arc welding with a phosphor bronze electrode. This procedure came under review because of the amount of time spent in straightening (to correct distortion), in grinding and cleaning the welds, and in removing spatter.

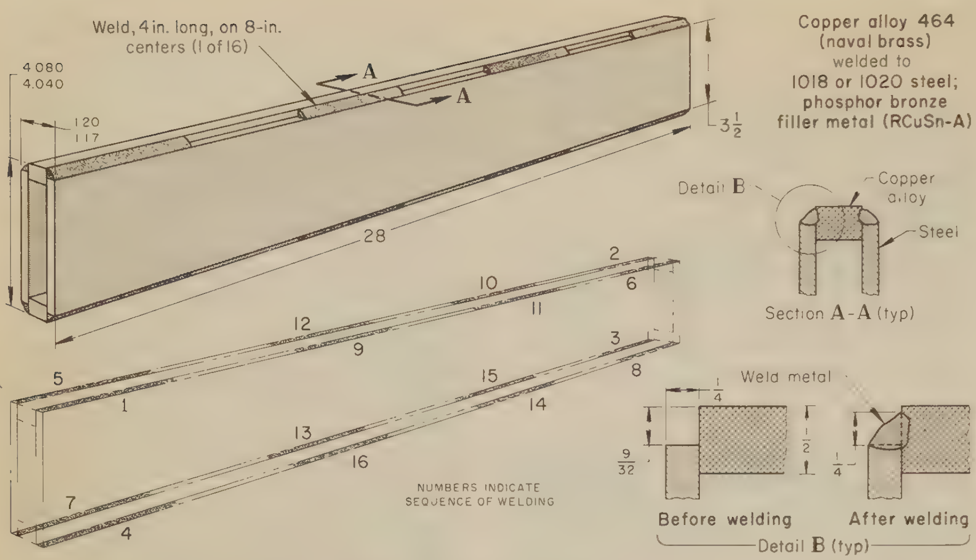
To eliminate the problems, the process was changed to gas tungsten-arc welding, using a revised procedure. Before welding, joint surfaces were cleaned by sanding and wiping with clean rags. The components were assembled in a fixture (jig) and mounted on a positioner to orient the assembly for flat welding. Joints were then tack welded, using the gas tungsten-arc process with argon shielding and phosphor bronze filler metal. (Although tack welding had not been used in the original procedure, it was specified here to help maintain alignment of the pieces during welding.) Then the joints were welded, using the same process and filler metal as for tack welding. Because of the large difference in melting temperature between the steel and the brass, the welding was started on the steel. This preheated the brass. Filler metal was then fed in at 6 to 8 in. per minute.

In the gas tungsten-arc process, instead of continuous fillet welds (as in the previous method), 16 intermittent fillet welds, 4 in. long on 8-in. centers, were deposited in a staggered sequence. The use of intermittent welds did not impair the strength of the assembly, because the service load on the welds was quite low. On the other hand, the intermittent welds greatly reduced heat input and distributed it favorably — both of which helped eliminate distortion. Also, the use of gas tungsten-arc welding eliminated the need for grinding and cleaning welds and removing spatter.

Details of the improved welding procedure are given in the table that accompanies Fig. 21, along with a comparison of time and cost for the original and the improved methods. As shown, gas tungsten-arc welding saved approximately two-thirds of the time and cost of shielded metal-arc welding, in addition to eliminating the distortion problem. Although part of the time and cost saving with gas tungsten-arc welding resulted because of the change from continuous to intermittent welds, the major portion was due to the elimination of the postweld cleaning and straightening operations.

Automatic Welding

Automatic gas tungsten-arc welding is used extensively. The degree of mechanization varies from the simple



Item	Shielded metal-arc	Gas tungsten-arc
Labor Time per Piece, Hr		
Welding	0.67	0.45
Grinding and cleaning	0.26	...
Straightening (est avg)	0.50	...
Total labor time per piece, hr	1.43	0.45
Cost per Piece		
Labor and overhead (at $9/hr)	$12.87	$4.05
Filler metal	4.73	1.89
Shielding gas	...	0.24
Total cost per piece	$17.60	$6.18

Conditions for Gas Tungsten-Arc Welding

Joint type	Corner
Weld type	Fillet
Process	Manual gas tungsten-arc
Electrode	1/16-in.-diam EWTh-2(a)
Welding torch	300-amp, water cooled
Filler metal	1/8-in.-diam RCuSn-A(b)
Shielding gas	Argon, 20 cfh
Welding position	Flat(c)
Current	Medium amp, dcsp(d)
Voltage	30 to 33 v
Arc starting	High frequency
Arc length	1/8 in., approx
Power supply	300-amp transformer-rectifier

(a) Taper ground. (b) Phosphor bronze. (c) With assembly in a jig and mounted on a positioner. (d) Equipment had a range selector for low, medium and high amperage.

Fig. 21. Boxlike weldment of steel and brass, for which change from continuous welds by the shielded metal-arc process to intermittent welds by the gas tungsten-arc process eliminated a distortion problem and saved time and cost (Example 135)

mounting of the welding torch in a bracket that moves over the workpiece (or in a stationary bracket, with the workpiece being moved under the torch), to a fully automatic operation that accomplishes the complete welding cycle (see Example 133). The degree of mechanization is usually determined by the number of identical welds to be made, and by the speed and quality desired. The aerospace industry uses automatic gas tungsten-arc welding extensively, not necessarily because of large quantities of production parts, but because the quality required for aerospace designs often can be achieved only with the control inherent in automatic welding. A typical example of this is the fabrication of large-diameter rocket-motor cases, in which longitudinal and girth welds are made by automatic welding techniques.

Mechanized welding is usually employed for metals that must be welded in a chamber, because it provides greater ability to manipulate the work within the chamber, compared with manual welding (see Example 133).

Equipment. Semiautomatic torches for gas tungsten-arc welding were introduced about 1952, but were never widely used. Essentially, a semiautomatic torch is an assembly of a hand-held water-cooled torch with an attachment that brings the filler metal (wire) into the arc area. The filler metal is fed to the torch through a flexible conduit by means of a motor-driven wire feeder. The wire feeder is controlled by a trigger switch on the torch. In theory, the filler wire fed from the torch helps propel the torch and establish travel speed. The wire is then melted by the arc and deposited in the joint. The introduction of gas metal-arc welding interrupted the full development of the semiautomatic gas tungsten-arc welding system, and it is now little used.

For automated welding systems, the torch is mounted in a mechanism for moving the work or the torch relative to one another. Specially designed torches are used; two types are available. One, the heavy-duty barrel type, is of metal construction and water cooled. It is equipped with a rack and is long enough to be adjusted and carried in a holder similar to that used for machine gas cutting. Barrel-type holders are fully insulated, can be used with various types of nozzles, and accommodate electrodes up to 18 or 24 in. long, with diameters of 0.040 to 1/4 in. Welding current may be up to 600 amp.

The second type of torch is also water cooled, but will not fit automatic gas-cutting equipment. These torches are usually made to accommodate shorter (7-in.-long) electrodes in a slightly smaller size range (0.020 to 3/16 in.). Welding current for these torches may be up to 500 amp. In addition, metal or ceramic nozzles can be used. These shorter holders require a special offset bracket for mounting.

Mechanized or automatic gas-cutting carriages are often used for moving the automatic torches. Special hardware and adapters are readily available. Automatic head controllers are also available. They will electronically maintain a preset arc voltage even though the surface of the work being welded varies substantially.

For completely automatic production-line welding of joints requiring the addition of filler metal, a wire feeder is added. An adjustable bracket is mounted at the torch to direct the "cold" (electrically neutral) filler metal into the arc area. This equipment is used for welding with direct current, straight polarity. The wire feed is adjusted to provide the amount of filler metal required — which is based on joint design, travel speed, welding current, and filler-wire size.

Examples of Practice. Changing from manual to mechanized welding usually requires a good knowledge of welding, a high degree of skill in machine design, and a high initial investment. These requirements necessarily increase with the degree of automation desired. Because of the availability of a wide variety of mechanical and electrical controls, operations of seemingly great complexity can often be automated. Because of its inherent arc stability, gas tungsten-arc welding is readily adapted to this type of control. Usually, if a repetitive operation can be manually fixtured and manually welded, it can be mechanized. And if the welding machine is used frequently, the initial investment often can be recovered in a short time, as in Example 136, which follows. Examples 137 and 138 in this section describe applications for which automatic gas tungsten-arc welding was advantageously employed. An application of automatic welding in a vacuum-purge chamber is described in Example 133. See also Examples 252 to 255 in "Arc Welding of Stainless Steel".

Example 136. Change From Manual to Automatic Welding for Increased Productivity (Fig. 22)

The four legs that constituted the supporting members of swivel-chair bases were made by blanking, forming and welding 0.057-in.-thick low-carbon steel sheet. Figure 22 shows the configuration of a typical leg, with its underside facing up to reveal the weld at the seam.

Originally, the seam was welded by manually clamping the piece in a fixture, to draw the edges closely together, and then fusing the seam with a hand-operated gas tungsten-arc torch. Although this method welded 39 legs per hour, it was too slow to satisfy increasing demands. Since the operation was simple, it was possible to develop a machine to solve the production problem without changing part design.

The operating cycle of the machine was initiated by inserting the workpiece into the clamping fixture. From this point on, the operator simply monitored the operation. The fixture automatically clamped the workpiece so that the sheared edges (burrs facing out) formed a tight square-groove butt joint. Next, the gas tungsten-arc torch started its traverse with a preflow of argon gas for shielding. A limit switch initiated the arc by closing the direct-current welding circuit, together with a superimposed high-frequency circuit used for arc starting only. Welding conditions are given in the table with Fig. 22. At the end of the 11-in. traverse, a second limit switch tripped the welding circuit. After a short argon postflow, the part was automatically ejected.

Since neither the mechanical strength of the joint nor the appearance of the weld

was critical, visual inspection was made for uniformly good appearance; rejection rate was less than 1%. Smooth-appearing welds with no need for cleanup were obtained more consistently than by manual welding.

With the change to automatic welding, not only did production rate increase, but it was soon found that one operator could easily manage two machines simultaneously. Operating two machines on this basis, production rate increased to 210 legs per hour. Although the two machines required an investment of $15,000, the entire cost was recovered in approximately 3 months.

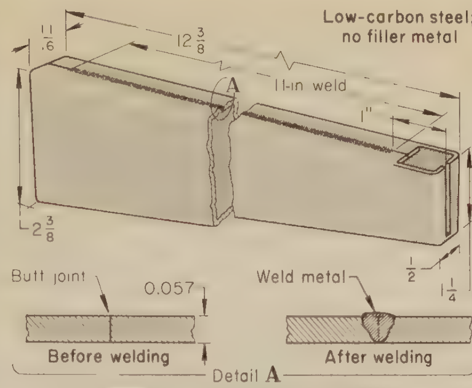
Example 137. Use of Automatic Welding To Reduce Production Costs (Fig. 23)

Originally, tractor engine hoods (Fig. 23a) were deep drawn from a single sheet of cold rolled 16-gage (0.060 in.) fully killed low-carbon steel of drawing quality. The front section (containing the headlight openings) was identical for all models, but the rear section (covering the radiator and air filter) differed in length and location of openings. To reduce tool and die costs and to eliminate problems in drawing, it was decided to draw the front sections separately and weld them to rear sections as needed.

Since finished hoods were under no appreciable stress but were painted and exposed to view, the objective was to obtain, at a high production rate, a uniformly low-profile weld that could easily be roll-planished and polished flush with the surface. It appeared that this objective could be reached best by using automatic, single-pass gas tungsten-arc welding on a butt joint, without filler metal.

In designing the machine for automatic welding, the major problem was how to position the workpieces. Welding the 33-in.-long seam entirely in the flat position was most desirable, but this would require considerable workpiece manipulation, which appeared too costly. To position the parts for welding up one side, across the top, and down the other side introduced a number of undesired welding variables, including nonuniform weld profile. Positioning the parts so that the joint lay in the horizontal plane meant welding in the relatively difficult horizontal position; however, this position made welding conditions essentially the same throughout the weld length. Locators and clamping fixtures could be made rigid, and only the torch and its supporting arm would be required to move. This positioning was adopted because it entailed minimum tooling expense and low cost for the automatic machine.

As shown in Fig. 23(b), the two portions of the hood were held in close alignment by clamping them against two vertically



Automatic Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Square groove
Electrode	1/8-in.-diam EWTh-2
Filler metal	None
Shielding gas	Argon, 15 cfh
Welding torch	500-amp, water cooled(a)
Current	150 amp, dcsp
Voltage	14 v
Arc length	3/32 in.
Power supply	550-amp transformer-rectifier with high frequency
Production rate	210 legs per hour(b)

(a) Ceramic cap. (b) Based on welding with two machines operated simultaneously by one operator.

Fig. 22. Swivel-chair leg that was welded automatically at 5½ times the production rate obtained in manual welding (Example 136)

spaced fixtures, made of a copper alloy. Clamping force was exerted by a vertical and a horizontal air piston. The vertical clamp forced the joint edges closely together; the horizontal clamp held the work metal against the fixtures (see section A-A in Fig. 23b). The torch was mounted on a spring-loaded slide, which in turn was mounted on a supporting arm connected to a centrally located drive shaft. As the drive rotated in the direction of welding, the slide was displaced in the radial direction by means of a stationary cam having a curvature identical with the joint. Once the torch was set in correct operating position, welding was accomplished automatically in a single pass. Because the speed changed through corner radii, microswitches tripped to start and stop a second speed, overriding straight-line speed control. For easy arc starting, an ultraviolet-ray lamp was aimed to create an ionized path at the torch tip.

Postweld operations included inspection, roll-planishing and polishing of the welded joint (see Fig. 23c) prior to painting. After welding, the joint was subjected to 100% visual examination for penetration and weld continuity. The slight deformation in weld shape (due to welding in the horizontal position) and minor surface porosity were corrected largely by planishing the weld to within a few thousandths of an inch from the surface of the sheet metal. During the polishing operation, the weld profile was made flush with the sheet-metal surface, and was carefully examined for depressions or porosity that remained.

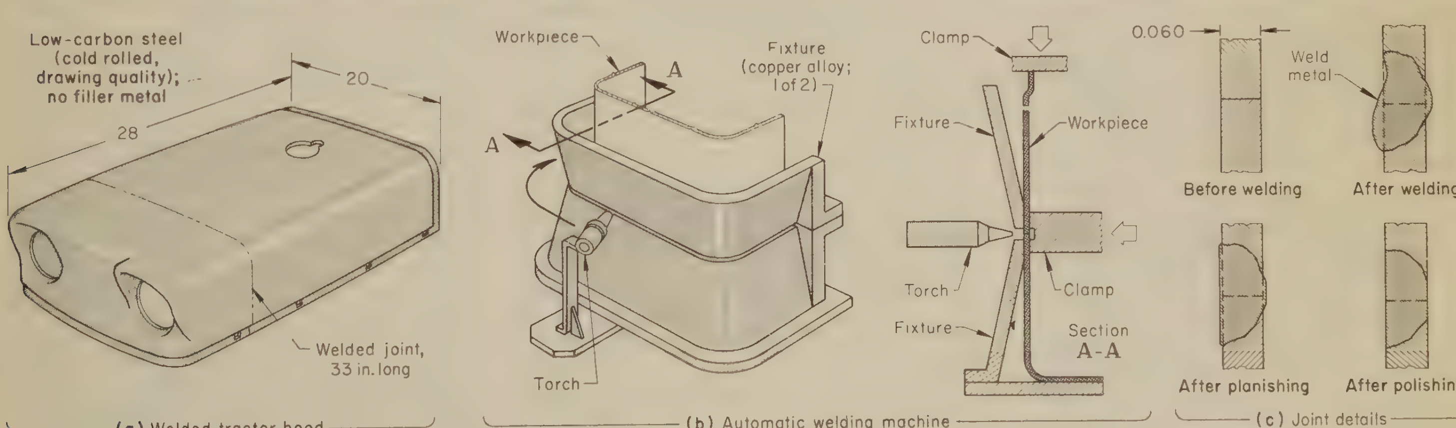
Automatic welding proved to be a successful substitution for the original method. Parts were produced with satisfactory appearance, at reasonable cost. Average floor-to-floor time for loading the machine, welding, and unloading was 2 min per piece. Other details of the welding operation are given in the table with Fig. 23.

Example 138. Simultaneous Welding of Four Box Corners at High Speed (Fig. 24)

Figure 24 shows a low-carbon steel enclosure for electrical controls, in the form of a rectangular open-top box, that was produced in sizes ranging from 2½ to 6 in. in depth, 5 to 36 in. in width and 8 to 36 in. in length. Thicknesses ranged from 0.030 in. to 0.078 in. These enclosures were produced by blanking, bending the four sides to form the box shape, and welding the four corner joints in the vertical position. Joint requirements called for a full-penetration seal weld having a smooth appearance suitable for painting. Aluminum-killed steel of drawing quality was selected to avoid weld porosity, since no filler metal was used.

To meet competitive prices on these products, a completely automatic setup, using high-speed welding, was constructed. The setup involved automatic sequencing of the production cycle, including initial fixturing of parts, synchronizing the simultaneous operation of four welding torches, and the final ejection of the welded product.

After forming, the enclosures were positioned and automatically clamped in a fixture consisting of twelve water-cooled copper chill bars, three bars being located at each of the four corners (see detail A in Fig. 24). Four water-cooled gas tungsten-arc welding torches, each having its own power supply, automatically advanced to welding position. At this point, a weld-sequence timer switched on the welding power. Each welding power supply was equipped with high frequency, for easy arc starting, and with upslope and downslope control. Upon completion of the welds, the enclosures were automatically ejected. Welds



Joint type	Butt
Weld type	Square groove
Process	Automatic gas tungsten-arc
Electrode	1/8-in.-diam EWTh-1(a)
Filler metal	None
Welding torch	Water cooled(b)
Shielding gas	Argon, 12 cfh
Current	190 amp, dcsp
Voltage	18 v
Power supply	300-amp transformer-rectifier(c)
Arc starting	Ionizing ultraviolet lamp
Welding position	Horizontal
Number of passes	One
Welding speed	30 ipm
Production rate	30 hoods per hour

(a) Tip tapered to 1/32-in. diameter. (b) Adjustably mounted. (c) Without slope or postsurge.

Fig. 23. Automatic welding of a two-piece tractor hood that formerly had been made in one piece by deep drawing (Example 137)

were spot checked by visual inspection for voids and general appearance as to smoothness and roundness. Additional welding details are given in the table with Fig. 24.

Spot Welding

Adaptation of the gas tungsten-arc process to spot welding permits automatic arc spot welding of sheet-metal assemblies where access to only one side of the joint is possible. The capabilities of this method are especially useful for welding of corrugated structures for aerospace applications.

Gas tungsten-arc spot welding may be automated to the extent determined necessary to produce quantity and quality welds. The process is used for spot welding of automobile bodies, double-wall structures, aerospace fuel ducts, brackets to thin-wall skins, and foil-thin skins to thicker materials.

Gas tungsten-arc spot welding is capable not only of making spot welds on overlapped sheets (considered as the conventional procedure), but also of producing short welds that join two abutting edges (see Example 139 and Fig. 25); the latter are actually intermittent square-groove welds.

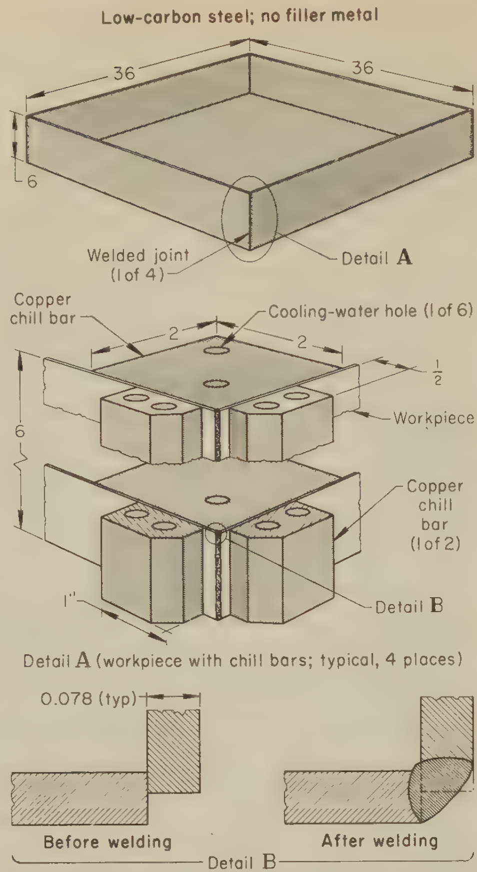
Equipment. An arc timer and a special torch (often called a gun) are the only additional pieces of equipment needed for spot welding. High-frequency stabilizing current is used to initiate the arc. Preflow and postflow of shielding gas are normally used.

The arc timer is usually built into power supplies designed for gas tungsten-arc welding, but external or auxiliary timers may be used. Arc time ranges from about ¼ sec to over 5 sec.

The welding torch is usually of pistol-grip design with a finger switch. Metal nozzles are used, because the nozzle is in contact with the work and is used to apply enough pressure to ensure close contact of the parts being spot welded together. Arc-spot torches are either air cooled or water cooled, depending on capacity and duty cycle.

Use of Filler-Metal Wire. Two major problems encountered in gas tungsten-arc spot welding are crater cracking and excessively concave weld surface. A modification of the process to overcome these problems is the addition of filler metal to the arc spot weld. Equipment has been developed to feed filler-metal wire into the arc area during the arcing period. The major requirement of the equipment is the sequencing of operations. A programed controller provides for control of gas flow, welding current, tapering (decay) of welding current, and wire feed. The nozzle of the torch is more complicated than the conventional type. Provisions are made for properly feeding the filler wire into the arc without fouling the electrode or sticking in the weld puddle. This process has not been widely adopted; it shows the most promise for spot welding aluminum in thicknesses greater than can normally be spot welded by resistance welding.

Example of Practice. The example that follows describes the use of gas tungsten-arc spot welding equipment and techniques for joining abutting edges by intermittent square-groove welds, in an application for which quality was critical.



Joint type	Corner
Weld type	Fillet
Process	Automatic gas tungsten-arc
Electrodes (4)	⅛-in.-diam EWTh-2(a)
Filler metal	None
Welding torches (4)	300-amp, water cooled(b)
Shielding gas	Argon, 10 cfh
Current (each circuit)	100-200 amp, dcsp
Voltage (each circuit)	30-34 v
Power supplies (4)	250-amp transformer-rectifier (constant current, high frequency)
Power control	Sequencer with slope control
Welding speed	200 ipm

(a) Taper ground to point. (b) With gas cup.

Fig. 24. Electrical-control enclosure that was automatically welded at all four corners simultaneously, using water-cooled copper chill bars as shown (Example 138)

Example 139. Rimmed vs Killed Steels for Spot Welding Collapsible Steering Columns (Fig. 25)

Steel quality proved critical in spot welding the longitudinal seams of collapsible steering columns made of 0.065-in.-thick, cold rolled 1006 or 1008 steel, perforated and roll-formed into tubes 2 in. in diameter by 30 in. long. As shown in Fig. 25, the perforated (collapsible) section of the steering column was joined with fourteen 0.08-in.-diam butt welds, and the two unperforated sections were joined with seven 0.25-in.-diam butt welds.

Performance specifications required that all welds remain intact when the column collapsed. In view of the collapsibility of the column, this requirement was not considered severe.

Because of the high production rate desired for this part, weld time had to be held to an absolute minimum — which was 15 cycles (¼ sec). With such a short weld time, any gas generated during welding was trapped in the weld, resulting in porosity. Since the welds were made by an arc discharge without added filler metal, cleanness of the base metal was an important consideration. Hot rolled steel was not considered, because of the presence of a thin layer of oxide.

Preliminary work on a rimmed cold rolled steel indicated that too much gas was generated. Therefore, an aluminum-killed cold rolled steel, known to be relatively gas-free, was selected for this application. Welds were made with no porosity. As production experience was gained, it was found that weld strength was more than adequate. To lower cost, a trial run was made using semikilled steel. Although some porosity appeared, the welds were strong enough to meet the performance specification. Substituting the semikilled for the fully killed steel resulted in a saving of 3¢ to 4¢ per piece.

An automated five-station setup was used for welding. The steering columns were clamped in a jawlike fixture that held the abutting seam edges in correct alignment and position for welding. The fixture-and-part assembly was then shuttled through the five stations, where selected welds were made by energizing prepositioned, gas-shielded tungsten electrodes. Welding was the same as conventional gas tungsten-arc spot welding, except that instead of being produced between lapped sheets, the spot welds were centered on the abutting seam edges; thus, they were not true spot welds, but were short intermittent tack-type groove welds. The need for five stations was determined by the proximity, size and distribution of the welds along the seam and, to some extent, by distortion effects.

After welding was completed, the columns were given a 100% visual inspection. The high production rate of 1200 pieces per hour (see table of welding conditions with Fig. 25) was not obtained without occasional problems. One problem was arc blow, which caused the weld to deviate from true center on the seam. Arc blow was minimized by machine design. In addition, because seam edges were given no special edge preparation, burrs on sheared edges sometimes interfered with weld deposition. This difficulty was overcome by tighter control over the shearing operation.

For details of a program established in one plant for control of thickness and properties of as-received base metal, and for determination of capabilities of welding machines, to improve the quality of spot welds made by several processes, including gas tungsten-arc welding, the reader is referred to Example 377 in the article on Resistance Spot Welding, in this volume.

Cost

For some applications, gas tungsten-arc welding may be the only technically acceptable welding process for the work metal, or for the conditions under which welding must be accomplished. Such restrictive considerations are more important than cost in the selection of the welding process.

On the basis of cost alone, the use of gas tungsten-arc welding is limited primarily by the cost of the inert gases used for shielding and by generally rather low production rates (compared with those obtained in other arc welding processes). The average cost of inert gases in cylinders is 7¢ to 10¢ per cubic foot at a flow rate of 10 to 15 cu ft per hour. On the other hand, this process in its simplest form requires only a manually operated torch and a gas regulator and flowmeter, in addition to the welding power supply. Accordingly, the initial capital outlay for this minimal equipment is relatively modest.

Gas tungsten-arc welding can be employed for production welding most economically in the joining of thin sections, particularly where square-groove

welds (no bevel) can be made and no filler metal is needed. Under such conditions, welding speeds of 150 in. per minute are easily achieved using relatively simple automatic equipment. In more specialized applications, gas tungsten-arc welding is used with more fully automated equipment incorporating automatic control and programing of arc conditions, speed of torch travel, and rate of filler-wire feed.

Manual gas tungsten-arc welding has a versatility and flexibility that, coupled with the low capital outlay involved, provides a most useful tool for job-shop maintenance and repair welding for which the work metal or other technical factors rule out the more commonly used and less costly processes. For example, gas tungsten-arc welding may be particularly desirable for rework or repair of production welds; for altering of parts machined incorrectly; for welding tubes to tube-sheet in heat exchangers; and for the root pass in pipe welding (see Example 128). In addition, this process is sometimes used for complete piping welds; for the repair of worn or broken dies; and for retrofit modifications of existing equipment or products.

The primary step in determining the cost of a gas tungsten-arc weld is to analyze the length of time required for making the weld, and the amount of filler wire required. This may be done by observing the actual job, by estimation from tables, or by estimation from past experience. Once these elements are determined, the cost of the weld can be figured if the purchase prices and rates of consumption are known. The methods for determining the cost of labor, gas, filler metal, electricity and electrodes are outlined in Table 10. A sample calculation of welding costs for a specific application is given in detail in Table 11.

When comparing the cost of gas tungsten-arc welding with the cost of other welding methods, it should be remembered that the cost and time for finishing the weld will be largely eliminated when gas tungsten-arc welding is used.

Table 10. Procedure for Determining Costs of Gas Tungsten-Arc Welding(a)

Labor Cost, \$ = (Time for job, minutes) × (1/60) × (Welder's hourly rate, \$)
Gas Cost, \$ = (Arc time, minutes) × (1/60) × (Gas flow rate per hour, cu ft) × (Cost per cubic foot of gas, \$)
Filler-Metal Cost, \$:
Automatic Welding = (Arc time, minutes) × (Feed rate per minute, in.) × (Wire weight per inch, lb) × (Wire cost per pound, \$)
Manual Welding = (Wire used, in.) × (Wire weight per inch, lb) × (Wire cost per pound, \$) (b)
Electric Power Cost, \$ = (Welding current, amp) × (Arc voltage) × (1/1000) × (Power cost per kwhr, \$) × (Arc time, minutes) × (1/60)
Electrode Cost = Approx 4% of gas cost

(a) No overhead or amortization of equipment is considered. See Table 11 for a sample calculation based on this procedure. (b) Or: total weight of wire used per job, in pounds, times cost of wire per pound.

Table 11. Cost Calculations for a Specific Weld, Using Procedure Shown in Table 10

Welding Conditions	
Work metal	Aluminum alloy, 1/16 in. thick
Type of weld	Butt
Process	Manual gas tungsten-arc
Current	70 amp
Voltage	10 v
Welding time	13 minutes
Arc time	10 minutes
Gas flow rate	20 cfh
Filler-metal wire	3/32-in.-diam ER4043
Weight of wire used	0.14 lb
Cost Items	
Labor	\$5.00 per hr
Electricity	\$0.03 per kwhr
Filler metal	\$1.40 per lb
Gas	\$0.10 per cu ft
Cost Calculations	
Labor (13/60 × \$5.00)	\$1.08
Gas (10/60 × 20 × \$0.10)	0.33
Filler metal (0.14 × \$1.40)	0.20
Electricity (70 × 10/1000 × \$0.03 × 10/60)	0.0035
Electrode (4% of \$0.33 gas cost)	0.0132
Total cost of weld(a)	\$1.63

(a) Total of items above; does not include overhead and equipment amortization, which may be the deciding factor in a cost comparison.

Safety

Gas tungsten-arc welding is no more hazardous than other welding processes if adequate precautions are observed with regard to eye protection, protective clothing, and ventilation.

Eye Protection. The filter-plate lenses used in helmets and face shields should be of the deepest shade that permits adequate visibility of the welding operation. (As a guide, AWS recommends shade No. 11 for gas tungsten-arc welding of nonferrous metals, and No. 12 for ferrous.) The use of medium-shade (No. 2) flash goggles is recommended in addition to the welding helmet for both the welder and other personnel present in the welding area.

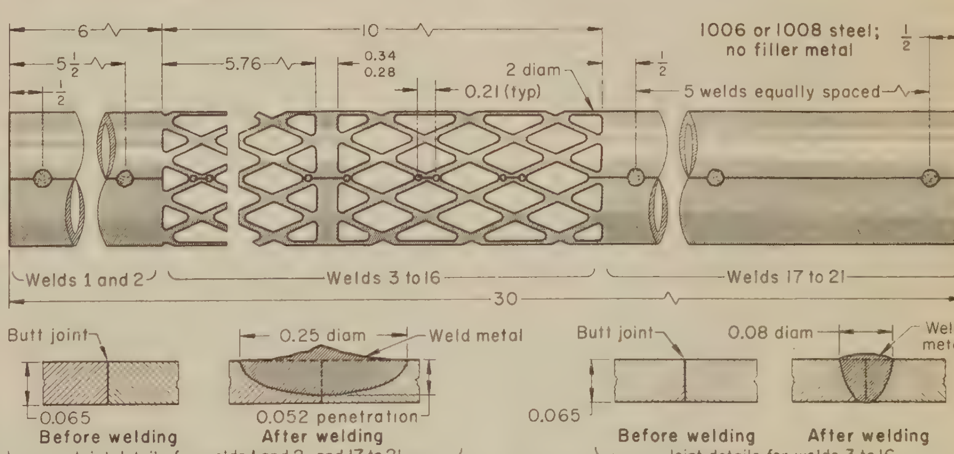
Protective clothing is needed to shield the welder from the intense arc radiation. The tungsten arc is fully exposed, and the ultraviolet and infrared radiations may produce an arc burn that resembles sunburn except that it is more severe. Dark-colored clothing is preferred to light, because the rays more readily penetrate light-colored fabrics. Light colors are also more reflective, and may cause eye burns even when a helmet is worn. Cotton fabrics should be avoided. Clothing should be made flame resistant by immersing it in sodium tetraborate or sodium stannate and ammonium sulfate solutions. Cuffless trousers should be worn to prevent entrapment of hot slag or spatter. Gauntlet gloves should be worn to protect the hands and wrists from arc burns and possible weld spatter.

Ventilation. Adequate ventilation that does not disturb the gas shield can be obtained by placing a low-velocity suction duct several inches away from the welding operation. Fans or drafts of over 50 sfm may blow the protective gas envelope away from the weld zone, causing oxidation of the heated metal.

During welding operations, ozone and noxious fumes are generated, which may become toxic in large concentrations. The fumes from some chlorinated solvents (three examples are carbon tetrachloride, trichlorethylene, and tetrachlorethylene), when exposed to a tungsten arc, form a toxic gas, phosgene, even at a long distance (hundreds of feet away) unless walls or baffles keep these fumes from the welding area.

Care should be taken when working with toxic metals. Air-supplied face shields or respirators may be required in confined areas that are not adequately ventilated. Argon or helium may displace the air that the welder requires for breathing.

Adequate ventilation is mandatory for all gas tungsten-arc welding. Detailed information concerning ventilation is contained in the American National Standards Institute publication Z49.1, "Safety in Electric and Gas Welding and Cutting Operations"; also suggested for reading is the American Welding Society pamphlet A6.1-66, "Recommended Safe Practices for Gas-Shielded Arc Welding".



Joint type	Butt (as-sheared, no burrs)
Process	Automatic gas tungsten-arc(a)
Electrode	1/8-in.-diam EWTh-2(b)
Filler metal	None
Welding torch	Water cooled, gas cup
Shielding gas	Argon(c)
Current, 0.08-in.-diam welds	200 amp, dcsp
Current, 0.25-in.-diam welds	300 amp, dcsp
Voltage	22 to 23 v
Arc starting	High-frequency pilot arc
Weld time	15 cycles(d)
Welding position	Flat
Power supply	300-amp transformer-rectifier(e)
Production rate	1200 pieces per hour

(a) Five-station automatic sequencing. (b) Tapered to 0.040-in. diam, for welds of both diameters. (c) Bulk; continuous flow. (d) For welds of both diameters; timer controlled. (e) Three-phase, with high frequency and timing controls.

Fig. 25. Collapsible steering column that was joined at 21 spots by automatic gas tungsten-arc welding (Example 139)

Table 12. Examples of Gas Tungsten-Arc Welding Presented Elsewhere in This Volume

Metal welded	Example
Low-Carbon and Medium-Carbon Steels	
1020	45
Low-carbon	123, 159
ASTM A266	193
Alloy Steels	
3120	158
4137H	162
4140	225
4335 mod	227
4340	225, 226
A2	166
D2	165
H11	205
T2	167
D-6ac	142, 201, 202, 203, 228
Maraging steel, 18% Ni	141
Stainless Steels	
301	261
304 and 304L	143, 243, 245, 246, 249, 270
305	262
316 and 316L	143, 253, 258, 259
321	254, 260, 263, 265
347	242, 244, 255, 262
410	141
430	251, 257
446	252
PH 14-8 Mo	250
PH 15-7 Mo	247
17-4 PH	256
17-7 PH	248, 259
AM-350	256
Heat-Resisting Alloys	
A-286	263, 282
Hastelloy C	275
Hastelloy X	277, 281
HS-21	288
HS-25	286, 287
Inconel 600	270, 279
Nickel alloy 718	263, 276
René 41	274
Waspaloy	271, 272, 273, 280
Refractory Metals	
Columbium alloy Cb-1Zr	289
Molybdenum alloy Mo-0.5Ti	290, 291, 292
Aluminum Alloys	
2014	318
2219	319, 320
5052	310
5083	311, 313
5086	311
5456	315
6061	311, 314, 317, 318, 321
6351	312
7075	321
7079	321
355	316
Copper Alloys	
110	114, 324, 326
120	325
122	323, 324
170	327, 328, 329
Copper Alloys (continued)	
172	328
175	334
210	324
220	324
230	324
260	324
442	323, 330
464	330
510	331
521	331
614	323
655	323
687	323
715	323
BeCu (1.7% Be) cast alloy	329
SAE 65 (phosphor bronze)	332
Alloy 9B (aluminum bronze)	333
Magnesium Alloys	
AZ31B	340, 341, 342, 343, 344
AZ91C	345, 346
AZ92A	347, 348, 349
EZ33A	350, 351
Nickel Alloys	
Mumetal	352
Nichrome	353
Nickel (99% Ni)	281, 353
4-79 Moly Permalloy	352
Titanium Alloy	
Ti-6Al-4V	141, 357, 358, 359, 360

Plasma-Arc Welding

PLASMA-ARC WELDING is an arc welding process in which the heat is produced by a constricted arc between a nonconsumable tungsten electrode and a workpiece (transferred arc), or between a nonconsumable tungsten electrode and a constricting orifice (nontransferred arc).

When an arc is established through a gaseous column separating two electrodes, some of the gas becomes ionized. This ionized material, called plasma, consists of free electrons, positive ions, and electrically neutral atoms. The plasma, or current-conducting, section of the arc is kept hot by the resistance heating effect of the current passing through it. Thermal ionization, the term employed to describe ionization that takes place in a high-temperature atmosphere, results from collisions of molecules and electrons in the gas and from radiation.

Plasma-arc welding is closely related to gas tungsten-arc welding (see the preceding article in this volume). Plasma is present in all arcs. If a constriction containing an orifice (nozzle) is placed around the arc, the amount of ionization, or plasma, is greatly increased. This results in higher arc temperature, a more concentrated heat pattern, and higher arc voltage than can be obtained with a nonconstricted arc.

Much of the text of this article is from an unpublished paper prepared for an ASM conference by N. F. Bratkovich, Section Chief, Joining Processes, Material Engineering Dept., Indianapolis Operation, Detroit Diesel Allison Div., General Motors Corp.

The examples in this article were contributed by members of six of the Metals Handbook welding committees.

For plasma-arc welding, constriction of the arc is produced by the design of the welding torch. Figure 1 shows the heat patterns and arc temperatures for a nonconstricted arc, used in gas tungsten-arc welding, and a constricted arc, used in plasma-arc welding.

Applicability

Plasma-arc welding is adaptable to both manual and automatic operation, and can be used to produce either continuous or intermittent welds. Welds may be made with or without the addition of filler metal. Plasma-arc welding is most often an alternative to gas tungsten-arc welding. It is sometimes competitive with oxyacetylene welding and electron-beam welding and occasionally with resistance seam welding (see section on Plasma-Arc Welding vs Alternative Processes, page 145).

Metals Welded. Plasma-arc welding is adaptable to joining carbon and alloy steels, stainless steels, heat-resisting alloys, refractory metals, copper alloys, nickel alloys, and titanium alloys. Aluminum alloys have been successfully plasma-arc welded, but this process has not been used to any significant extent for welding these alloys.

Metals that have low melting temperatures and low boiling temperatures, such as lead and zinc, are not amenable to plasma-arc welding.

Welding Positions. Plasma-arc welding is generally considered to be an all-position process, depending somewhat on whether or not filler metal is used.

Work-Metal Thickness. Plasma-arc welding is well adapted to welding thin sections. Because of the stability and dimensional control provided by the constricted arc, foils as thin as 0.001 in. have been welded in production, with current as low as 1½ amp. However, welding of such thin metal requires extremely precise fixturing and the closest control possible. The minimum work-metal thickness is usually considered to be 0.003 in., although 0.002-in.-thick stainless steel, for use in convoluted bellows, has been successfully welded for several years.

The maximum work-metal thickness is usually determined by cost. When work-metal thickness exceeds ¼ in., other welding processes are usually faster and more economical. However, when quality requirements are high, plasma-arc welding is sometimes used for the root pass, and a faster, cheaper process, such as submerged-arc welding or gas metal-arc welding, is used for succeeding passes.

Advantages. The constricted arc used in plasma-arc welding offers several advantages over the nonconstricted arc used in gas tungsten-arc welding:

1. Concentration of energy is greater.
2. Arc stability is improved, particularly at low current levels.
3. Heat content is higher.
4. The plasma has higher velocity.
5. There is less sensitivity to variations in arc length.
6. Tungsten contamination is eliminated.
7. Less welder dexterity is required for manual welding.
8. Solid backing is not required for obtaining complete penetration, because the keyhole technique can be used (Fig. 3).

In comparison with gas tungsten-arc welding, plasma-arc welding per-

mits greater welding speed and closer control of the process, and can be used for welding thinner sections.

Disadvantages. The main disadvantages of plasma-arc welding, compared with gas tungsten-arc welding, are:

1. Higher cost of equipment (generally two to five times as much)
2. Short life of the orifice body
3. Need for greater welder knowledge, although not necessarily greater dexterity on the part of the welder
4. High rate of inert-gas consumption.

Fundamentals of the Process

In plasma-arc welding, a tungsten electrode is used, as in gas tungsten-arc welding. Two separate streams of gas are supplied to the welding torch. One stream surrounds the electrode within the orifice body and passes through the orifice, constricting the arc to form a jet of intensely hot and fast-moving plasma. This gas must be inert and is usually argon.

The other stream of gas, the shielding gas, passes between the orifice body and the outer shield cup. It prevents the molten weld metal and the arc from becoming contaminated by the surrounding atmosphere. An inert gas, such as argon, can also be used for shielding, but nonoxidizing gas mixtures, such as argon with 5% hydrogen, have often proved advantageous (see the section in this article on Orifice and Shielding Gases, page 141).

Distance from orifice to work is commonly maintained at about 3/16 in.; this distance is less critical than the distance from the end of the electrode to the work in gas tungsten-arc welding. A distance of 1/8 to 1/4 in. does not significantly affect welding results.

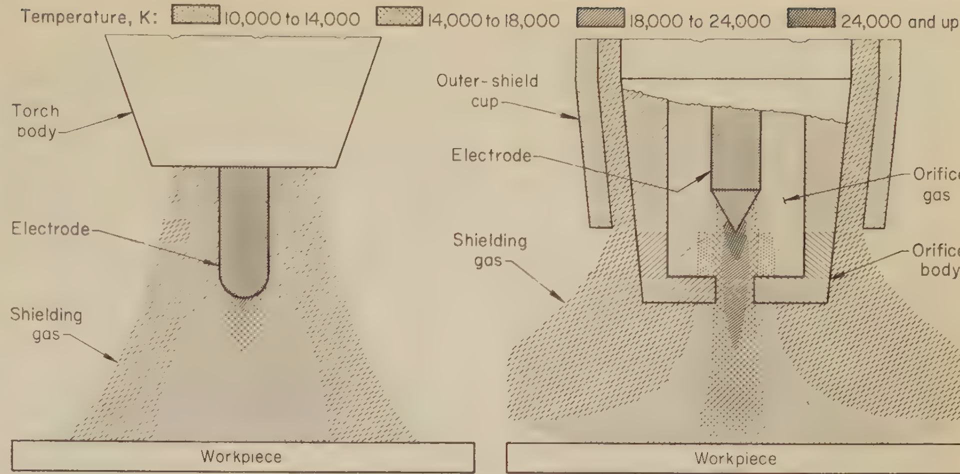
Arc Types. Two arc systems are used to generate plasma: a transferred arc and a nontransferred arc. In the transferred type, the arc is established between the electrode and the workpiece. A nontransferred arc is established between the electrode and the inside of the orifice body, and heat is delivered to the work by the hot plasma only.

For welding, the transferred arc is used almost exclusively, because the arc delivers more heat to the work. This system is shown in Fig. 2. Note that the negative lead from the power supply is connected to the electrode and the positive lead is connected to the workpiece. This electrical hookup is called straight polarity. The positive lead is also connected, through a resistor, to the orifice body. This permits establishment of a pilot arc at a low current level, as needed.

The nontransferred arc may be used in special welding applications when a lower energy concentration is desirable. Its main use is in joining or cutting of nonconductive work materials. For a nontransferred arc, there is no electrical connection to the work.

Heat-Energy Concentration. In concentration of heat energy, the constricted plasma arc falls between the unconstricted arc used for gas tungsten-arc welding and the electron beam in electron-beam welding. Heat-energy concentrations for the three processes, based on width of fusion zone in 1/4-in.-thick 410 stainless steel, are shown in Fig. 3. Normally, the plasma-arc and gas tungsten-arc processes yield similar welds if the melt-in (conventional fusion) mode of welding is used. However, with the plasma-arc process, a special technique called keyhole welding is possible, and it yields the deeper, narrower penetration shown in Fig. 3 (see the description of this technique under "Keyhole Welding", page 142).

Current. Plasma-arc welding can be done at considerably lower current than gas tungsten-arc welding, often at a current as low as 1 amp, and sometimes at 0.1 amp. High current is also used. The line of demarcation between high-current and low-current operation is arbitrary, although usually low-current welding is considered to be that done in the range of 0.1 to 100 amp, and high-current welding to be that done with current above 100 amp — usually 100 to 500 amp. Welding current seldom exceeds 500 amp and is usually less than 400 amp.



(a) Nonconstricted arc (gas tungsten-arc welding) (b) Constricted arc (plasma-arc welding)

Nonconstricted Arc		Constricted Arc (3/16-In.-Diam Orifice)	
Shielding gas	Argon, at 40 cfh	Shielding gas	Argon, at 40 cfh
Current	200 amp	Current	200 amp
Voltage	15 v	Voltage	30 v

Fig. 1. Comparison of a nonconstricted arc used for gas tungsten-arc welding and a constricted arc used for plasma-arc welding, showing the effect of constriction on temperature and heat pattern

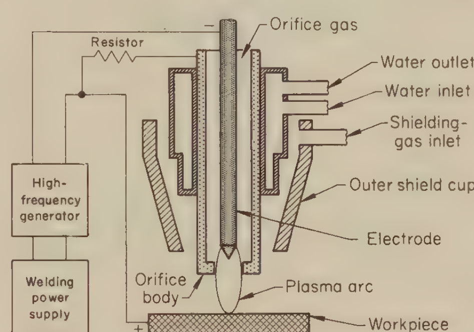


Fig. 2. Schematic diagram of a high-current plasma-arc welding system, using a transferred arc

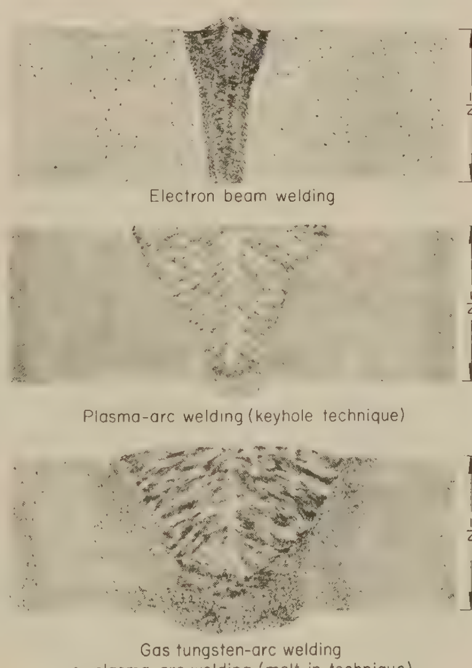


Fig. 3. Typical fusion-zone widths for electron beam welding, plasma-arc welding (keyhole technique), and gas tungsten-arc welding

Power Supply

Plasma-arc welding is done almost exclusively with straight-polarity direct current from a constant-current power supply (drooping voltage). Reverse polarity causes excessive deterioration of the electrode. The direct current can be rectified from alternating current or supplied by a motor-generator or an engine-driven generator. Power supplies for arc welding are described in the articles on Shielded Metal-Arc Welding, Gas Metal-Arc Welding, and Gas Tungsten-Arc Welding, in this volume.

Rectifiers having an open-circuit voltage of 65 to 80 v are most commonly used as the basic unit. Power supply units for gas tungsten-arc welding can be converted for plasma-arc welding. Also, power supplies that have appropriate adjustments are made especially for plasma-arc welding. The nature of the application usually dictates the adjustments required. For instance, power supplies with current slope control are required for welding circumferential

joints where a keyhole must be initiated and closed out gradually (see the section on Keyhole Welding in this article). Programing equipment that controls current slope and gas flow at desired intervals is available.

An essential piece of equipment for plasma-arc welding is a power supply for starting the arc.

Arc Initiation. Because the electrode tip is within the orifice body (Fig. 2 and 4), the arc cannot be started by touching it to the workpiece, as in gas tungsten-arc welding; other means must be employed for arc initiation.

For low-current welding (under 100 amp), a system such as that shown in Fig. 4 is most commonly used. In this system, a separate direct-current power supply (identified as "Pilot-arc power supply" in Fig. 4) is connected to the electrode and to the copper orifice body. By means of this supplementary power supply, a pilot arc is initiated between the electrode and the interior of the orifice body. To start the pilot arc, the electrode is advanced by means of an adjusting screw until it touches the bottom of the orifice body. The electrode is then withdrawn to a distance that is specified on the particular torch, in terms of number of turns of a vernier-type thumbscrew.

The pilot arc is maintained during short periods of downtime, during which time a small amount of argon is flowed through the orifice while the pilot arc is operating.

When the pilot arc has been established, the contactor to the lead attached to the workpiece (Fig. 4) is closed, and the hot ionized orifice gas forms a conductive path between the electrode and the workpiece when the orifice of the torch is held close to the work. The conductive path results in striking of an arc between the electrode and the workpiece.

This method of starting the arc for low-current welding provides a smooth start and eliminates the tracks and etch marks that can result from high-frequency starting. However, some systems use a high-frequency generator to initiate the pilot arc.

For high-current welding, the arc is usually started by a high-frequency current superimposed on the main welding current, as in gas tungsten-arc welding. The high-frequency current is obtained from a separate supply, as shown in Fig. 2.

Welding Torches

Torches for plasma-arc welding are more complex than those for gas tungsten-arc welding, because separate passages are required for the orifice gas and the shielding gas, and because the orifice body must be protected by a water-cooled jacket.

A torch for manual plasma-arc welding is shown in Fig. 5. It is provided with a handle for holding, a means for securing the tungsten electrode in position and conducting current to it, separate passages for the orifice and shielding gases, a water-cooled orifice body (copper), and an outer shield cup (usually of ceramic material). Torches for automatic plasma-arc welding are similar to manual torches.

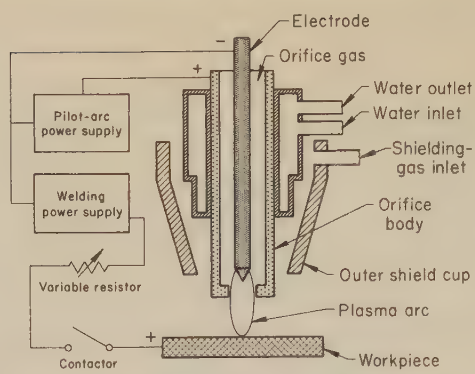


Fig. 4. Schematic diagram of a low-current plasma-arc welding system, using a transferred arc

Table 1. Typical Relationships of Orifice Diameter to Current and to Flow Rate of Orifice Gas

Orifice diameter, in.	Current, amp	Flow rate of orifice gas, cfh
0.030	1 to 25	½
0.052	20 to 55	1
0.086	40 to 100	1½

Table 2. AWS Classifications and Composition Limits for Tungsten Arc Welding Electrodes (AWS A5.12-69)

AWS classification	Tungsten, % min(a)	Thoria, %	Zirconia, %	Other, % max(b)
EWP	99.5	...	...	0.5
EWTh-1 ...	98.5	0.8-1.2	...	0.5
EWTh-2 ...	97.5	1.7-2.2	...	0.5
EWTh-3(c) .	98.95	0.35-0.55	...	0.5
EWZr	99.2	...	0.15-0.40	0.5

(a) By difference. (b) Total. (c) EWTh-3 is a tungsten electrode with an integral lateral segment throughout its length that contains 1.0 to 2.0% thoria; average thoria content of the electrode is as shown in this table.

Controls for gas and welding current are usually separate from the torch and are operated either by a foot control or automatically.

Orifice Diameter. Table 1 shows the relation of orifice diameter to current, and the increase in orifice-gas flow with increase in orifice diameter. An orifice diameter as small as 0.030 in. may be used with very low current.

Multiple-Port Orifice Bodies. Most plasma-arc torches have only one port (orifice) in the orifice body, as shown in Fig. 2, 4 and 5, but torches having multiple ports are available and have certain advantages.

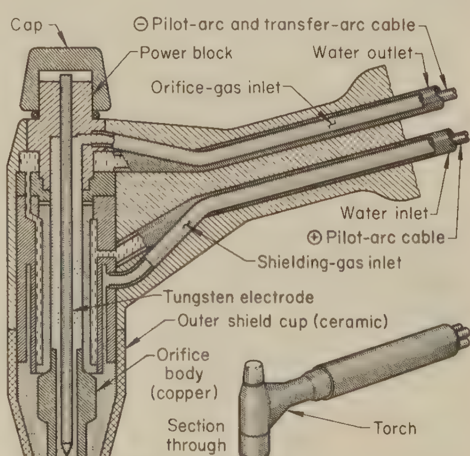


Fig. 5. Typical torch for manual plasma-arc welding

Various types of multiple-port orifice bodies, including those with holes arranged in rows, circles, and other geometric patterns, have been evaluated. The most successful design is one that has the central orifice bracketed by two smaller ports, with a common horizontal centerline for all three ports (Fig. 6). These two ports, each of which has about one-fourth the cross-sectional area of the main orifice, convey a portion of the orifice gas, and change the normally circular heat pattern from the plasma arc into an oval or elongated shape. When the multiple-port orifice body is aligned so that the common centerline of the ports is perpendicular to the weld joint, the arc is elongated in line with the joint. The elongated heat pattern permits greater welding speed and produces welds with narrower heat-affected zones. In one application, in welding a square-groove butt joint in ⅛-in.-thick stainless steel, maximum welding speed with a single-port orifice body was 12 in. per minute, but use of a multiple-port orifice body permitted an increase in speed to 18 in. per minute. With both the single-port and multiple-port orifice bodies, the weld was made with a current of 180 amp, orifice-gas flow of 15 cfh, and shielding-gas flow of 35 cfh.

Orifice-Body Life. The relatively short life of the orifice body in the plasma-arc torch has prevented a more widespread use of plasma-arc welding. Deterioration of the orifice body is due to arcing between the electrode and the area within the orifice body near the orifice and to the intense heat generated by the plasma arc. Orifice-body life is generally less with small torches (those that operate at less than 100 amp), because water cooling is less effective than with large torches.

Occasionally, orifice bodies have deteriorated to such an extent that they were no longer usable after only a few minutes of arc time. However, this is unusual. In one large aircraft plant, in girth welding of titanium, using a 250-amp current, orifice-body life is usually 24 hr of arc time.

To prolong the life of orifice bodies, several approaches have been tried. One is to design the bodies so that the critical area is an insert that can be quickly changed. This greatly reduces cost compared with replacing the entire orifice body. Also, because the distance between the end of the tungsten electrode and the nearest point on the inside of the orifice body is critical, controlling this distance to the optimum value helps to prolong the life of the orifice body. This optimum distance varies for different sizes and designs of torches. The setting that should be used is marked on each torch. Usually, this distance is controlled by an adjusting screw on the torch. On some torches, gages that are inserted through the orifice are used as a means of setting the electrode.

Electrodes

The nonconsumable electrodes used in plasma-arc welding are made of tungsten of commercial purity (99.5%

W) and of tungsten alloyed with thoria or zirconia. The five electrode compositions listed in Table 2 are used for both plasma-arc welding and gas tungsten-arc welding.

The tungsten-thoria electrode EWTh-1 is often preferred for plasma-arc welding, but all of the grades listed in Table 2 have been successfully used.

The EWP, or pure tungsten, electrodes have lower current-carrying capacity than the tungsten-thoria and tungsten-zirconia electrodes. They have good resistance to contamination. Compared with EWP electrodes, tungsten-thoria electrodes have higher electron emission and higher current-carrying capacity, and generally longer life. Tungsten-zirconia electrodes (EWZr in Table 2) are preferred where tungsten contamination of the weld must be kept at a minimum.

Standard diameters and lengths of tungsten electrodes are given in Table 3. Because the current used in plasma-arc welding seldom exceeds 500 amp, the 5⁄32-in.-diam electrode is the largest commonly used. Table 4 lists typical ranges of current used with the various diameters of electrodes.

Electrode Shape. The arcing end of an electrode used for plasma-arc welding is ground to an included angle of approximately 60°, and the tip is flattened slightly. The diameter of the flat area is not critical; it is generally about 1⁄32 in. maximum for 1⁄8 or 5⁄32-in.-diam electrodes and proportionately less for smaller-diameter electrodes.

Orifice and Shielding Gases

Usually, the same gas is used for the orifice gas and for shielding. This is done to avoid variation in the consistency of the arc effluent, which occurs if two different types of gas are used.

Argon is a suitable orifice and shielding gas for welding all metals, but it does not necessarily produce optimum results for all metals. Argon is used for welding carbon steel, high-strength steel, and reactive metals such as titanium alloys and zirconium alloys.

Addition of hydrogen to the argon orifice gas produces a hotter arc and more efficient heat transfer to the workpiece, and higher welding speeds are obtained for a given arc current. The amount of hydrogen that can be used is limited, because excessive hydrogen may cause porosity in welds. The ability to use a higher percentage of hydrogen without inducing porosity depends on the techniques used and on the thickness of the metal being welded. Hydrogen is extremely detrimental in welding reactive metals such as titanium and zirconium alloys, because it results in embrittlement.

Argon-hydrogen mixtures are commonly used as the orifice gas and shielding gas for welding stainless steel (see Table 7). Permissible percentages of hydrogen usually vary from 1 to 5% in welding section thicknesses up to approximately 0.375 in. (see Tables 6 and 7). In some applications, the gas mixture may contain as much as 15% hydrogen (note Example 146).

Addition of helium to argon also produces a hotter arc for a given arc current, but at least 50% helium is needed

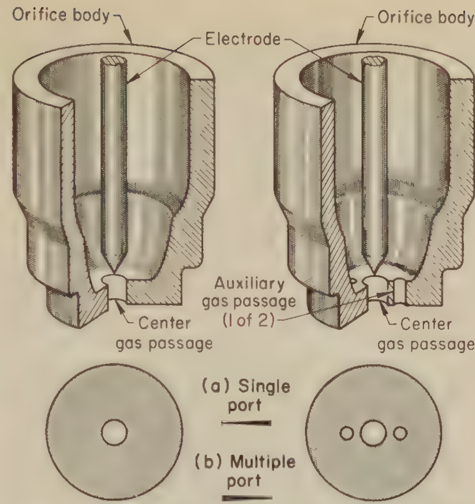


Fig. 6. Single and multiple-port orifice bodies

in a gas mixture before a significant change can be detected. Mixtures containing more than 75% helium behave about the same as pure helium, and have the same limitations. Mixtures containing 50 to 75% helium have been employed in making keyhole welds in titanium, where the use of this gas mixture permits higher travel speed than when pure argon is used and prevents concave root surface, which is sometimes obtained with pure argon.

The use of pure helium as an orifice gas increases the heat load on the torch and reduces its service life and current-carrying capacity. Because helium has a low mass, it is difficult to obtain a keyholing action at reasonable

Table 3. Standard Diameters and Lengths of Tungsten Arc Welding Electrodes (AWS A5.12-69)

Standard diameters, in.	Tolerance on diameter, in.	Standard lengths, all diameters(a), in.	Tolerance on length, in.
Diameters		**Lengths**	
0.010	±0.001	3, 6, 7	±1⁄16
0.020	±0.002	12, 18, 24	±1⁄8
0.040, 1⁄16, 3⁄32, 1⁄8, 5⁄32, 3⁄16, 1⁄4	±0.003		

(a) 0.010-in. electrodes are also available as coils.

Table 4. Typical Ranges of Current for Plasma-Arc Welding With Tungsten Electrodes(a)

Electrode diameter, in.	Current (dcsp), amp	Electrode diameter, in.	Current (dcsp), amp
0.010	Up to 15	1⁄8	250 to 400
0.020	5 to 20	5⁄32	400 to 500
0.040	15 to 80		
1⁄16	70 to 150		
3⁄32	150 to 250		

(a) For electrodes EWP, EWTh-1, EWTh-2 and EWTh-3

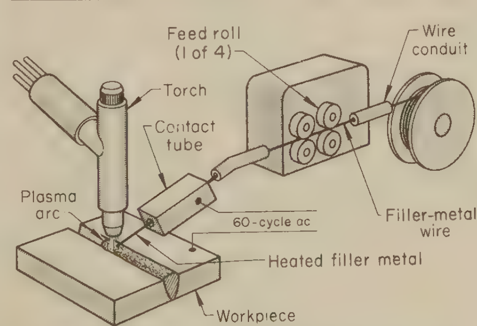


Fig. 7. A system for automatically feeding hot filler-metal wire to the weld puddle

flow rates. Therefore, pure helium is not used for making keyhole welds.

For further information on gases used in welding, and their storage and handling, see the articles on Gas Tungsten-Arc Welding and Gas Metal-Arc Welding in this volume.

Filler Metals

The use of filler metal in plasma-arc welding depends on whether or not additional metal is needed. Filler metal is available in wire form in virtually any composition needed. For all but special applications, filler metals are the same as those used for gas tungsten-arc welding (see section on Filler Metals on page 127 in the article on Gas Tungsten-Arc Welding in this volume).

For manual welding, the filler metal (generally in straight lengths that can be conveniently handled) is fed into the leading edge of the weld puddle. The height at which the filler metal is fed is not critical in plasma-arc welding, because the design of the torch ensures that there is no danger of its touching, and thereby contaminating, the electrode.

Automatic Welding. Most plasma-arc welding applications that use a current of more than 100 amp are automatic, at least to the extent of having the torch held mechanically. When filler metal is used in automatic welding, it is usually fed to the weld puddle by a constant-speed wire-feeding system (see the section on Wire-Feed Systems in the article on Gas Metal-Arc Welding in this volume). The rate of feed must be determined for each new application by experimentation.

Hot-Wire Systems. Welding speed can be increased by preheating the filler-metal wire before it enters the weld puddle. The usual method is to pass electrical current through the wire for a short distance before the wire enters the weld puddle. Figure 7 shows a hot-wire-feeding system commonly used for automatic welding.

Accessory Equipment

Accessory equipment required for plasma-arc welding, including jigs, fixtures, and the various types of positioners and handling devices, is generally the same as for other shielded-arc welding processes (see the sections dealing with these subjects in the articles on Shielded Metal-Arc Welding, Gas Tungsten-Arc Welding, and Gas Metal-Arc Welding in this volume).

Joint Preparation

Joint designs for workpieces up to about 0.060 in. thick are generally the same for plasma-arc welding as for gas tungsten-arc welding. Square-groove butt joints are commonly used for most workpieces in the above thickness range. Also, the conventional (not keyholing) method of welding is usually employed, and fusion is accomplished in the same manner as with gas tungsten-arc welding. Root opening and misalignment are less critical in plasma-arc welding, because of the "stiffness" of the plasma arc and its insensitivity to voltage changes.

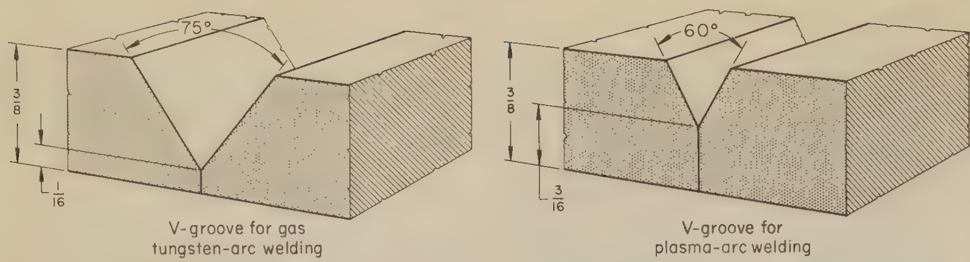


Fig. 8. Comparative typical joints for a V-groove weld to be made in ⅜-in. metal by gas tungsten-arc welding and by plasma-arc welding

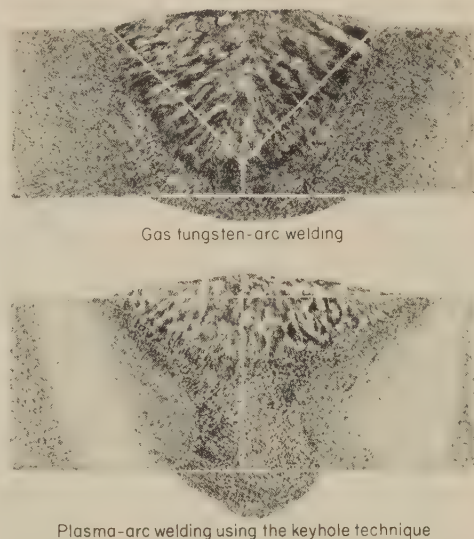
Edge-Flange Welds. For joining workpieces 0.002 to 0.010 in. thick, melting down of an edge-flange is commonly used. In effect, this technique at least doubles the thickness at the weld joint of the metal being welded. The pieces to be welded can be flanged on a roll flanger. A typical correlation between metal thickness and flange height is presented in Table 5.

Butt Joints in Thin Metal. Low-current plasma-arc welding has been successfully applied to stainless steels. Table 6 lists typical conditions for making low-current butt welds in thin stainless steel, either manually or with mechanized equipment.

Square-Groove Butt Joints. For joining workpieces in the thickness range of 0.060 to 0.250 in., the keyhole technique is usually employed (see the section on Keyhole Welding in this article). For some metals, such as titanium alloys, the keyhole technique can be used for thicknesses up to ½ in. without providing a V-groove (Table 7). The keyhole technique often permits welding of metals up to ¼ in. thick in one pass, with or without filler metal. However, for welding thicker metal (and sometimes for metal less than ¼ in. thick), a more uniform weld is obtained by using at least two passes, often the first without filler metal and the second with filler metal.

Machined-groove joints are usually required for the plasma-arc welding of workpieces ¼ to 1 in. thick, but because of the greater penetration of the plasma arc, compared with the gas tungsten arc, the groove depth can be much less. Consequently, the weld can be completed in fewer passes, and with less filler metal. Joint preparation required for plasma-arc welding and gas tungsten-arc welding of a V-groove is compared in Fig. 8.

Figure 9 compares plasma-arc welding and gas tungsten-arc welding for joining ¼-in.-thick type 410 stainless steel. For gas tungsten-arc welding, it was necessary to make a deep V-groove to leave a small root face (about 1/16 in. thick) that the arc could penetrate. The weld was then completed by making one root pass (without filler metal) and two filler-metal passes. For plasma-arc welding, using the keyhole technique, no joint preparation was required and the weld was completed with one root pass and one filler-metal pass. The arc time per 100 in. of weld in the table that accompanies Fig. 9 shows plasma-arc welding to be approximately four times as fast as gas tungsten-arc welding. An additional saving is obtained in reduced joint-preparation time.



Item	Gas tungsten-arc welding	Plasma-arc welding
Joint preparation	Scarf V-groove	None
Number of passes:		
Fusion	One	One
Filler metal	Two	One
Travel speed, ipm	4	10
Arc time per 100 in. of weld, minutes	75	20

Fig. 9. Joints welded in ¼-in.-thick type 410 stainless steel by the gas tungsten-arc process and by the plasma-arc process using the keyhole technique

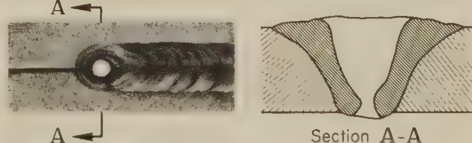


Fig. 10. Appearance of a keyhole weld in ¼-in.-thick stainless steel plate

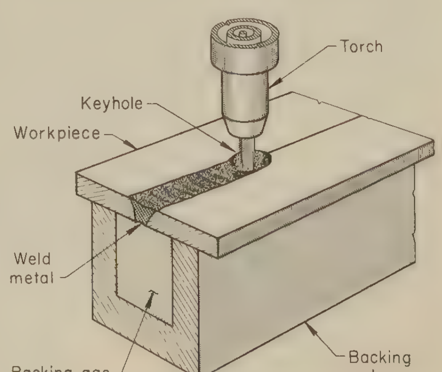


Fig. 11. Typical backing used with the keyhole technique

Keyhole Welding

Because of the intense heat and mechanical force of the plasma arc, the keyhole technique can be used with plasma-arc welding. A hole is produced at the leading edge of the weld puddle by the force of the plasma arc displacing the molten metal, allowing the arc to pass completely through the workpiece. As welding progresses, surface tension causes the molten metal to flow in behind the hole to form the weld bead. A keyhole weld produced in butt welding ¼-in.-thick stainless steel, as revealed photographically from above the weld and schematically at a cross section through the keyhole of the workpiece, is shown in Fig. 10.

The major advantages of the keyhole technique are the ability to penetrate rapidly through relatively thick root sections and to produce a uniform underbead without mechanical backing. Also, the ratio of the depth of penetration to the width of the weld is much higher, resulting in a narrower weld and heat-affected zone (see Fig. 3) Presence of the underbead is proof of complete joint penetration and simplifies weld inspection. Because of the precise control that is required, keyhole welding is usually done automatically. However, a successful keyhole weld can be produced manually by a skilled welder.

The keyhole technique can be applied to steel and stainless steel in the thickness range of 0.060 to 0.250 in. — total thickness of plate or thickness of root face for thicker plates with prepared joint edges. For metals that have lower density or greater surface tension in the molten state, such as titanium alloys, the keyhole technique can be employed for thicker sections, often up to 0.600 in.

Backing Requirements. The weld puddle of a plasma-arc keyhole weld is supported by the surface tension of the molten metal. It is not necessary, therefore, to employ close-fitting backing bars, which affect chill and ability to hold assembly tolerances. However, as in gas tungsten-arc welding, shielding gas is generally required on the back side of the weld to protect the molten underbead from atmospheric contamination. A backing as shown in Fig. 11 provides a duct for flow of the shielding gas at the weld root. This type of backing supports and aligns the workpiece, contains backing gas, and provides a vent space for the plasma jet. The groove is generally about ¾ in. wide and 1 in. deep.

Starting a Keyhole Weld. When welding metal less than ⅛ in. thick, longitudinal and circumferential keyhole welds can be started at full operating current, travel speed, and orifice-gas flow. The keyhole is developed with little or no disturbance in the weld puddle, and the weld surface and underbead are left smooth.

The operating currents and orifice-gas flows required to weld metal more than ⅛ in. thick generally produce a plasma arc that is likely to gouge or tunnel underneath the molten metal just prior to piercing through the joint. Because this gouging action may cause porosity and severe surface irregulari-

Table 5. Correlation of Metal Thickness and Flange Heights for Edge-Flange Welds

Metal thickness(t), in.	Height of flange(h), in.
0.002	0.004 to 0.010
0.005	0.010 to 0.025
0.010	0.020 to 0.050

Table 6. Conditions for Low-Current Plasma-Arc Welding of Butt Joints in Thin-Section Austenitic Stainless Steel(a)

Section thickness, in.	Current (dcsp), amp	Welding speed, ipm
0.001	0.3	5
0.003	1.6	6
0.005	2.0	5
0.010	6.0	8
0.030	10.0	5

(a) Orifice gas, argon at 0.5 cu ft per hour; orifice diameter, 0.030 in. Shielding gas, 99% argon – 1% hydrogen.

ties, starting tabs are used whenever possible to establish the keyhole off the workpiece. When welding heavy circumferential joints, a smooth transition from shallow penetration to a keyhole can be accomplished with a programed increase in welding current and orifice-gas flow. A typical slope-up control cycle for current and gas flow for starting a keyhole weld is shown on the left-hand side in Fig. 12. These functions are performed automatically by commercial welding controls.

Terminating a Keyhole Weld. If the welding current is turned off abruptly at the end of the weld, the keyhole will not close. This is no drawback if the weld can be stopped on an end tab, but if end tabs cannot be used, the keyhole can be closed by use of a slope-down control to reduce the welding current and orifice-gas flow gradually, as shown on the right side of Fig. 12. The net effect of a programed reduction in orifice-gas flow and welding current is to reduce the arc force and heat input and allow the molten metal to flow gradually into the keyhole and solidify.

In the event of a power failure or other malfunction that would cause welding to stop before the weld is completed, the keyhole would be left in the weldment. This hole can be filled in by repositioning the plasma-arc torch several inches behind the hole, recycling the control to make a new start and running over the original keyhole. The only indication that a repair has been made is a slight sink in the surface of the weld, which is filled in by the next pass.

Typical Operating Conditions for Various Metals

Table 7 gives typical operating conditions for plasma-arc welding of carbon and alloy steels, stainless steel, titanium, copper and brass. The same gas is recommended for orifice gas and shielding gas. Except for 0.375-in. stainless steel and 0.600-in. titanium, a square butt joint can be used, and except for 0.125 and 0.250-in. copper, the keyhole technique is employed for all root passes. After a root pass is deposited by plasma-arc welding, filler metal can be deposited by any suitable welding process.

Carbon and Alloy Steels. Typical operating conditions for plasma-arc welding of a low-carbon steel, a medium-carbon alloy steel, and a high-strength alloy steel, in different thicknesses, are given in Table 7. The high-strength steel (D-6ac) requires preheating (to 600 F) and postheating (at 750 F for 1 hr).

Stainless Steel. Typical conditions for plasma-arc welding of various thicknesses of stainless steel are shown in Tables 6 and 7. For all thicknesses, the electrode tip is ⅛ in. from the nearest point on the inner surface of the orifice body; orifice-to-work distance is 3⁄16 in.

The use of the keyhole technique on square butt joints in stainless steel is usually limited to metal less than 0.375 in. thick. However, 0.375-in. stainless steel can be fused by this technique if all welding conditions are closely controlled. Suitable conditions for a typical application include: travel speed, 8 in. per minute; current, 250 amp at 38 volts; orifice gas, 99.5% argon – 0.5% oxygen at 15 cfh; and shielding gas, 99.5% argon – 0.5% oxygen at 40 cfh. Even slight variations in these conditions can produce unsatisfactory welds, and so keyhole welding of square-groove butt joints in 0.375-in. stainless steel is not recommended. (Table 7 specifies a 60° included angle V-groove with a 3⁄16-in. root face for plasma-arc welding of 0.375-in. stainless steel.)

Titanium Alloys. One of the major applications of plasma-arc welding is

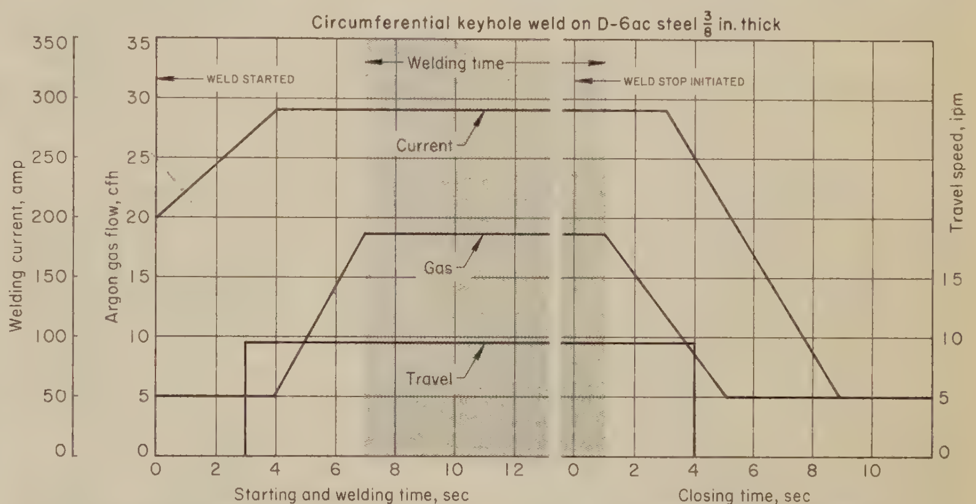


Fig. 12. Slope-control pattern for welding current and orifice-gas flow for starting and terminating a keyhole weld in ⅜-in. D-6ac steel. This is typical of slope-control patterns for welding other thicknesses of other metals.

Table 7. Typical Operating Conditions for Plasma-Arc Welding of Four Classes of Metals

Thickness, in.	Travel speed, ipm	Current (dcsp), amp	Arc voltage, v	Gas	Gas flow, cfh: Orifice gas	Gas flow, cfh: Shielding gas	Joint type	Technique(a)
Carbon and Low-Alloy Steels								
0.125 (1010)	12	185	28	Argon	13	60	Square butt	Keyhole
0.170 (4130)	10	200	29	Argon	12	60	Square butt	Keyhole
0.250 (D-6ac)	14	275	33	Argon	15	60	Square butt	Keyhole(b)
Stainless Steel(c)								
0.093	24	115	30	95% A – 5% H_2	6	35	Square butt	Keyhole
0.125	30	145	32	95% A – 5% H_2	10	35	Square butt	Keyhole
0.187	16	165	36	95% A – 5% H_2	13	45	Square butt	Keyhole
0.250	14	240	38	95% A – 5% H_2	18	50	Square butt	Keyhole
0.375:								
Root pass	9	230	36	95% A – 5% H_2	12	45	V-groove(d)	Keyhole
Filler pass	7	220	40	Helium	25	175	...	Filler(e)
Titanium Alloy(f)								
0.125	20	185	21	Argon	8	60	Square butt	Keyhole
0.187	13	175	25	Argon	18	60	Square butt	Keyhole
0.390	10	225	38	75% He – 25% A	32	60	Square butt	Keyhole
0.500	10	270	36	50% He – 50% A	27	60	Square butt	Keyhole
0.600	7	250	39	50% He – 50% A	30	60	V-groove(g)	Keyhole
Copper and Brass								
0.093 (copper)	10	180	28	Argon	10	60	Square butt	Keyhole(c)
0.125 (copper)	10	300	33	Helium	8	60	Square butt	Melt-in(h)
0.250 (copper)	20	670	46	Helium	5	60	Square butt	Melt-in(h)
0.080 (70 Cu – 30 Zn)	20	140	25	Argon	8	60	Square butt	Keyhole(c)
0.125 (70 Cu – 30 Zn)	16	200	27	Argon	10	60	Square butt	Keyhole(c)

(a) Orifice-to-work distance is 3⁄64 in. for carbon and alloy steels, and 3⁄16 in. for the other metals welded. A multiple-orifice torch is used. (b) Preheat to 600 F; postheat at 750 F for 1 hr. (c) Backing gas required. (d) 60° included angle; 3⁄16-in. root face. (e) 0.045-in.-diam filler-metal wire fed at 60 ipm. (f) Backing gas and trailing gas shield required. (g) 30° included angle; ⅜-in. root face. (h) Conventional fusion technique and graphite backup were used.

the joining of titanium alloys. Keyhole welds can be made through thicker square butt joints in titanium than in stainless steel and low-carbon steel, because titanium has a lower density. As with gas tungsten-arc welding, plasma-arc welding requires backing gas and a trailing gas shield to prevent atmospheric contamination of the weld bead and the adjacent base metal.

Copper and Brass. Keyhole welds are difficult to make in copper thicker than 0.093 in., because the high thermal conductivity of copper makes it necessary to use such high currents in welding thicker sections that a large weld-puddle area melts and droops down before a keyhole can be formed. Conditions for melt-in fusion welds are shown for metal thicknesses of 0.125 in. and greater in Table 7. Best results have been obtained in welding deoxidized copper; porosity is a relatively common occurrence when welding electrolytic tough pitch copper.

Manufacture of Stainless Steel Tubing

Continuously formed stainless steel pressure tubing conforming to ASTM A312 is made from strip rolled into tube form and butt welded, using the plasma-arc process, generally without filler metal. Installation of plasma-arc equipment in tube mills has resulted in substantially increased welding speed, compared with gas tungsten-arc welding. A comparison of average welding speeds for gas tungsten-arc welding and for plasma-arc welding on tubing of various wall thicknesses is shown in Table 8. Plasma-arc welding shows the greatest speed advantage on thicker-wall tubing. In addition, the rejection, or repair, rate when using plasma-arc welding is lower than when using gas tungsten-arc welding on thick-wall tubing, because of the uniform penetrating power of the plasma arc.

A schematic view of plasma-arc tube welding is shown in Fig. 13. Weld-bead shape and reinforcement are controlled by adjusting four variables: the welding current, the location of the arc relative to the centerline of the pressure rolls on the tube mill, the force exerted by the pressure rolls, and the backing-gas pressure inside the tube.

In beginning a production run, the arc is started and a keyhole is established approximately 1 in. ahead of the centerline of the pressure rolls. Excessive weld metal (reinforcement) at the top and bottom of the tube joint (Fig. 14a) indicates that the weld bead is too hot when it reaches the pressure point between the rolls and is, therefore, soft enough to be upset. This condition can be corrected by moving the torch farther ahead of the pressure rolls, allowing more time for the weld puddle to cool before it comes under forging pressure. If there is not enough reinforcement at the top of the joint (Fig. 14b), the torch should be moved closer to the pressure rolls. Pressure-roll force can also be increased or decreased to change the amount of weld reinforcement.

If excessive drop-through occurs (Fig. 14c), it can be corrected by increasing the backing-gas pressure. The backing gas is confined between plugs or diaphragms mounted on a pipe or lance inside the tube. Backing-gas pressure can be controlled by connecting a hose to the backing-gas chamber and exhausting the gas into a beaker or tube of water. Gas pressure is increased until bubbles appear in the water. Thereafter, pressure in the chamber will depend on how deeply the hose is immersed in the water.

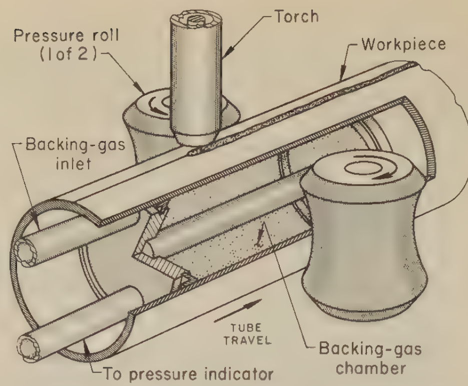


Fig. 13. Setup for welding longitudinal seams in stainless steel tubes, employing internal backing with inert gas

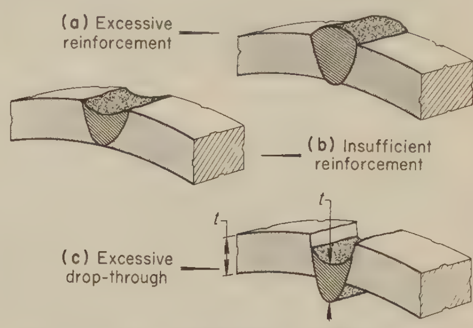
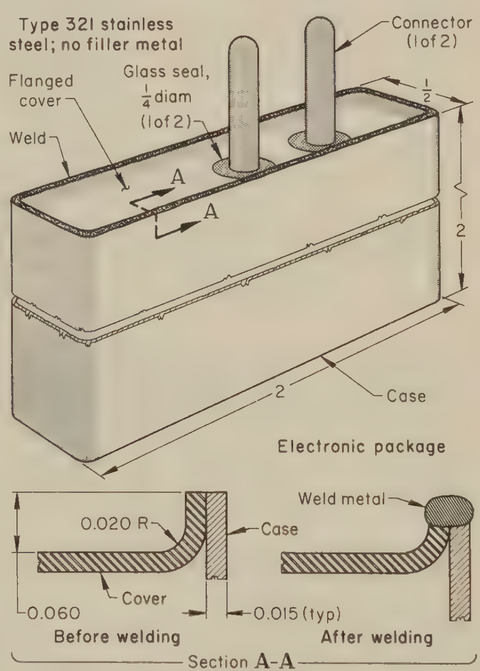


Fig. 14. Three undesirable conditions that are likely to be encountered in plasma-arc tube welding. See text for measures for correcting these conditions.



Conditions for Plasma-Arc Welding

Joint type	Edge
Weld type	Corner flange
Filler metal	None
Orifice gas	Argon, at 0.6 cfh
Shielding gas	95% A – 5% H_2, at 25 cfh
Orifice diameter	0.030 in.
Power supply	1 to 10 amp dc (with continuous high-frequency pilot circuit)
Current	5 amp, dcsp
Welding speed	5 ipm

Fig. 15. Electronic package that was plasma-arc welded to fuse a thin corner joint (Example 140)

Plasma-arc tube welding, unlike gas tungsten-arc tube welding, does not require arc-voltage control or automatic adjustment of orifice-to-work distance. This may greatly reduce the cost differential for equipment between the plasma-arc and gas tungsten-arc processes. Constant travel speed for the tube and good joint fit-up are essential for good-quality welds.

When tube diameter is 1 in. or less, the speed obtainable using plasma-arc welding is about the same as for gas tungsten-arc welding. For making this size of tube, a V-groove is formed as the edges of the strip are brought together. Keyholing, with its accompanying speed advantage, becomes impractical, because for the maximum wall thickness that would prevail for a 1-in.-diam tube there is not enough metal at the joint to support the molten weld puddle.

Circumferential Pipe Welding

Plasma-arc welding has been used to make circumferential joints in stainless steel pipe and in pipe of some other materials, in the horizontal and vertical pipe positions. This type of weld would normally be made by multiple-pass gas tungsten-arc welding, using a backing ring and filler-metal on a prepared joint. The use of plasma-arc welding permits keyhole welding of square-groove butt joints in one pass in pipe of 0.090 to 0.250-in. wall thickness. On pipe with wall thickness from 0.250 to 0.375 in., a V-groove with a 60° included angle and a root face half the thickness of the wall is used. This type of prepared joint requires two passes — a root pass using the keyhole technique, and a second pass using filler-metal wire. Slope control for welding current and orifice-gas flow is employed, to start and terminate the keyhole weld (Fig. 12).

Welding of Vessels

Welding of circumferential joints in tanks or vessels is an extension of the technique used to weld circumferential pipe joints. The vessel must be positioned and rotated so that the joint is in the horizontal position.

Plasma-arc welding on a vessel, involving the joining of girth seams on a D-6ac steel missile case, is described in Example 142 in this article.

Cost

Whether or not plasma-arc welding will be more expensive than another welding process will be determined only by careful evaluation of the application and the welding processes.

Equipment. Plasma-arc welding equipment is two to five times more expensive than gas tungsten-arc welding equipment of the same capacity, but is far less costly than electron-beam welding equipment of the same capacity.

Maintenance cost is greater for plasma-arc welding than for other arc welding processes. Frequent replacement of orifices is the principal contributor to the high maintenance cost of plasma-arc welding equipment.

Productivity capability of plasma-arc welding is high, and its potentiality for high production must be evaluated before it can be determined whether or not the high cost of equipment would be justified. In applications where plasma-arc welding is up to four times as fast as alternative processes, equipment costs are rapidly amortized if production quantities are high.

Several examples in the next section of this article show time and cost savings resulting from the use of plasma-arc welding in preference to an alternative process. One of them (Example 147) involves the production of about five million parts per year.

Plasma-Arc Welding vs Alternative Processes

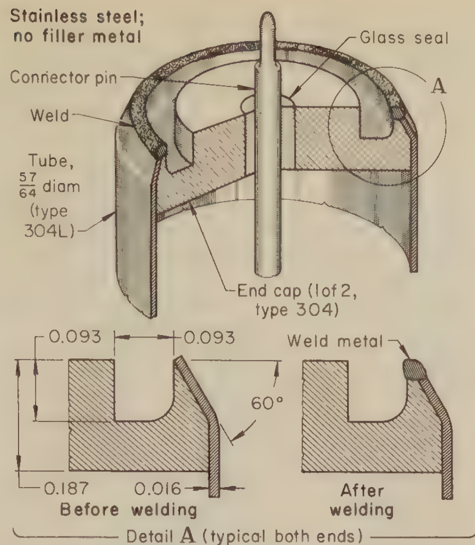
Plasma-arc welding is most often an alternative to gas tungsten-arc welding, of which it is a refinement. In other applications, plasma-arc welding competes with such widely different processes as electron-beam welding, oxyacetylene welding, or resistance seam welding. The examples that follow compare plasma-arc welding with these processes for specific applications.

Example 140. Plasma-Arc Welding vs Gas Tungsten-Arc Welding for Manual Fusion of Thin Joints (Fig. 15)

Enclosures for small electronic and electromagnetic devices were made of a thin stainless steel case into which was fitted a reverse-flanged cover containing glass-insulated connector pins. The enclosures were hermetically sealed by fusing the outer edge to form a corner weld (Fig. 15). The procedure was set up for manual welding by clamping the fitted stainless steel cases in the copper-faced jaws of a small, movable bench vise.

Originally, the weld was made by using a small gas tungsten-arc torch at low amperage. Manual seam tracking was difficult and tedious because the low amperage, needed to avoid overheating, required holding the arc length to within about 1/32 in. Small variations resulted either in stubbing the electrode tip or breaking the arc. As a result, arc restrikes, tip dressing and leaky welds were frequent. When amperage was increased to permit a longer arc, overheating often damaged the glass seals.

These problems were overcome to a large extent by changing over to a small plasma-arc unit designed for operation at approximately 1 to 10 amp. The lightweight torch (about 3 oz heavier than, and roughly the same size as, the gas tungsten-arc torch) had a 0.030-in.-diam orifice. This torch produced a shielded plasma column with an effective operating length of 1/8 to about 3/8 in., when used in the transferred-arc mode at 5 amp. The arc was initiated in the nontransferred mode — that is, as a pilot arc in a high-frequency circuit between the tungsten electrode and a copper anode within the torch body. When the torch nozzle was brought within operating distance, the dc welding circuit was closed by transfer of the arc to the grounded workpiece.



Conditions for Automatic Plasma-Arc Welding

Joint type	Edge
Weld type	Edge-flange
Number of passes	One
Welding position	Flat
Fixtures	Clamping jig; rotating positioner; fixed torch mount
Torch	10 amp, water cooled
Electrode	0.020-in.-diam EWTh-2
Filler metal	None
Orifice gas	Argon, at 0.68 cfh
Shielding gas	95% A – 5% H_2, at 20 cfh
Orifice-to-work distance	0.090 to 0.120 in.
Power supply	10-amp, 110-v (max) control unit
Current	5 amp, dcsp
Voltage	50 v
Welding speed	3 ipm
Preheat, postheat	None

Fig. 16. End cap in place on small electrical component, showing cap and joint design used for plasma-arc welding (Example 143)

After welding, the arc returned to the nontransferred mode.

Because of arc-length tolerance, manual welding was easier to control. Low heat input avoided damage to the glass seals, while the absence of frequent starts and stops resulted in better weld quality. Productivity increased, largely due to fewer rejects. The plasma-torch electrode required occasional dressing because of arc erosion, but dressing because of base-metal contamination was eliminated. Welding details are given in the table with Fig. 15.

Table 8. Average Speed for Fabricating Stainless Steel Tubing by Gas Tungsten-Arc Welding and by Plasma-Arc Welding

Wall thickness, in.	Welding speed, ipm: Gas tungsten-arc	Welding speed, ipm: Plasma-arc	Increase with plasma-arc welding, %
0.109	26	36	38
0.125	22	36	64
0.154	20	36	80
0.216	8	15	88
0.237	6	14	134

Example 141. Welding Speed — Plasma-Arc Welding vs Gas Tungsten-Arc Welding (Table 9)

Three metals used for aerospace components were welded by plasma-arc and gas tungsten-arc processes to compare times required for making welds. Samples welded were: 1/4-in.-thick type 410 stainless; 1/4-in.-thick maraging steel (18% Ni); and 0.095-in.-thick titanium alloy Ti-6Al-4V.

Welding conditions and results are given in Table 9. Plasma-arc welding took a fifth to a tenth as long to complete 100 in. of weld as gas tungsten-arc welding, partly because fewer passes were required and partly because travel speed was greater.

Example 142. Plasma-Arc Welding vs Gas Tungsten-Arc Welding for Making Missile Cases of D-6ac Alloy

Missile-case assemblies comprised five cylindrical sections 10 ft in diameter by about 10 ft long, and two hemispherical end domes. Each cylindrical section was fabricated from plate 3/8 in. thick by 9 ft wide by 32 ft long. The plate was formed into a cylinder and welded longitudinally. The 10-ft-diam hemispherical forgings were then welded to the ends of the cylinders.

Gas tungsten-arc welding, the process originally qualified for use in making the missile cases, required five passes with filler metal to complete a single circumferential butt joint, using a single-V groove with a 90° included angle, and a 0.060-in. root face. Maximum travel speed for any pass was about 5 in. per minute, and more than 14 hr of arc time was required to weld a single cylinder (one longitudinal weld and two circumferential welds). The welding operation was further complicated by the need for a 650 F preheat, joint tolerance and fit-up problems resulting from the size of the weldment, deterioration of ceramic-coated backing bars, and by the need for interpass cleaning.

Plasma-arc welding was used to fabricate a prototype cylinder. This technique employed a single-V groove with a 60° included angle and a 3/16-in. root face. A weld was completed in two passes, the root pass being made without filler metal, at a travel speed of 10 in. per minute, and the cover pass, with filler metal, at about 6 in. per minute. Because the underbead of the root pass was only about 5/32 in. wide, accurate following of the joint seam was essential. Total arc time to weld a single cylinder was about 4¼ hr, as compared with more than 14 hr for gas tungsten-arc welding. Filler-metal requirements were reduced, interpass cleaning time was a quarter that required for gas tungsten-arc welding, joint penetration was consistent, backing-bar problems were eliminated, and quality and mechanical properties of the welds met all specification requirements. However, plasma-arc welding was not used, because production of the missile cases was almost completed.

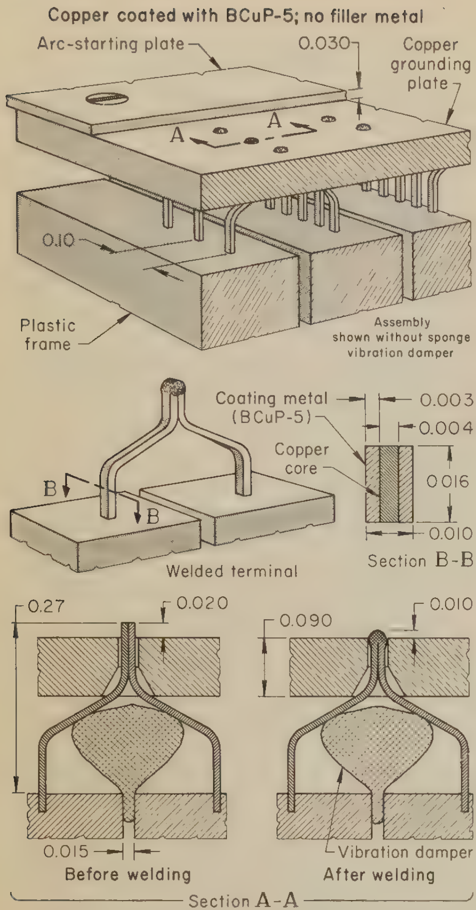
Example 143. Change to Plasma-Arc Welding From Gas Tungsten-Arc Welding for Attaching Tube End Caps (Fig. 16)

A delicate electrical component required hermetic seals between two end caps and a tube section (Fig. 16). Each end cap contained a connector pin insulated from the

Table 9. Plasma-Arc Welding vs Gas Tungsten-Arc Welding for Making 100-In. Welds in Three Aerospace Metals (Example 141)

Condition	410 stainless steel: Plasma-arc	410 stainless steel: Gas tungsten-arc	Maraging steel, 18% Ni: Plasma-arc	Maraging steel, 18% Ni: Gas tungsten-arc	Titanium alloy Ti-6Al-4V: Plasma-arc	Titanium alloy Ti-6Al-4V: Gas tungsten-arc
Thickness of metal, in.	0.250	0.250	0.250	0.250	0.095	0.095
Number of passes	1	2	1	3	2(a)	5(b)
Current, amp	240	170 to 200	240 to 260	180 to 200	90 to 175	120 to 175
Travel speed, ipm	12	4	12 to 13	4	15	6
Time per 100 in. of weld, minutes	8.3	50	7.4	75	13.4	83.5

(a) One keyhole welding pass and one filler-metal pass on the outside of a rocket-motor case. (b) One root pass without filler metal and two passes with filler metal on the outside of a rocket-motor case. The root pass was back gouged, and two filler passes were made on the inside.



Conditions for Automatic Plasma-Arc Welding

Joint type	Edge
Weld type	Edge-flange
Filler metal	None
Orifice gas	Argon, at 16 cfh
Shielding gas	Argon, at 15 cfh
Orifice-to-work distance	3/16 in.
Power supply	10-amp rectifier
Current	7 amp, dcsp
Arc starting	Pilot, self regulated
Welding speed	40 ipm

Fig. 17. Setup for welding terminal joints for a computer memory-grid array by plasma-arc welding, and appearance of welded terminal (Example 144)

cap by a glass seal and joined to an internal circuit by wrapped and brazed wires. Originally, the part was designed for a single-pass weld by gas tungsten-arc welding at each end. For this process, end caps did not have the heat-barrier groove and rolled-over edge shown in Fig. 16.

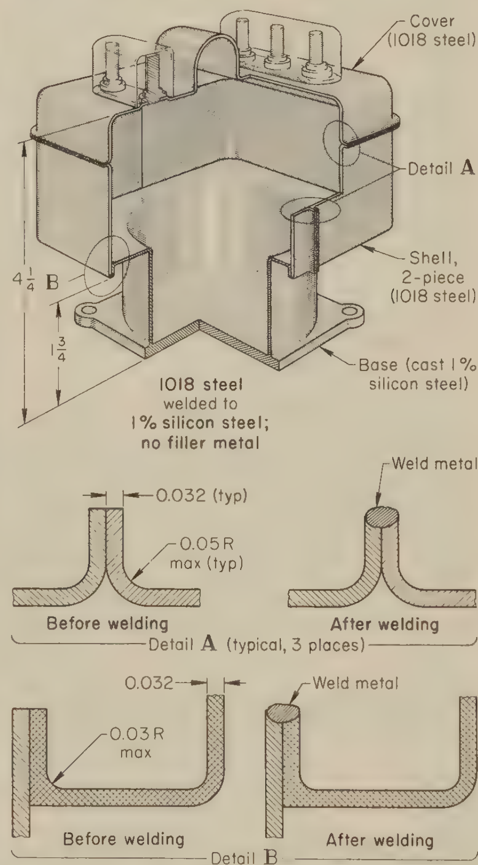
The part was fixtured for rotation about its vertical axis under a stationary electrode holder and the edge between the tube and cap was gas tungsten-arc welded. Several serious problems arose. Because a low-heat-input arc was essential in order to avoid overheating the glass seal, very precise electrode positioning was needed to maintain stability of the arc operating on low amperage. Also, to ensure proper electrical grounding of the two parts during welding, machining tolerances on the end cap and roundness tolerances on the tube were extremely close. When the welds made by this procedure were leak tested, about 80% were rejected; 30% could be salvaged by rewelding. Because rejection rate was too high, this welding procedure was abandoned.

Plasma-arc welding, using a new joint design, was tried. By using a very small plasma-arc torch, a much greater arc-length tolerance was obtained. End caps were beveled to permit the tube to be rolled over the edge, thus forming a tight mechanical joint more tolerant of dimensional variations. In addition, a groove was cut in the end caps to isolate the welded edges and to provide a longer heat path to the glass seal and a greater area for heat dissipation by radiation and convection. The groove also reduced restraint to shrinkage of the weld metal when the assembled relay housings were cooled.

The same clamping fixture, turntable and torch mount were used as with gas tungsten-arc welding. New equipment comprised a low-current plasma-arc welding unit, separate gas cylinders for orifice and shielding gases, and a plasma-arc torch.

The end caps were preplaced in the tube, the tube assembly was loaded in the fixture, the torch was positioned at an angle of 45° from vertical, and the weld was made. After one revolution of the work, the arc was continued for an overlap of about ⅛ in., after which the current was shut off by a foot control. The part was turned over, and the operation was repeated on the other end. Additional details for plasma-arc welding are given in the table that accompanies Fig. 16.

After assembly with other components, each unit was tested with air at 300 psi while immersed in water, and with a halide leak detector, using a mixture of 75 lb Freon and 300 lb air. Use of plasma-arc welding and the new joint design decreased rejections to 3%.



Joint type	Edge
Weld type	Edge-flange; corner-flange
Fixtures	Clamping jigs for tack welding and final welding; copper chill strip
Welding position	Flat
Electrode	0.040-in.-diam EWTh-2
Filler metal	None(a)
Orifice gas	Argon, at 0.6 cfh
Shielding gas	Argon, at 5 cfh; helium, at 20 cfh
Orifice diameter	5/16 in.
Orifice-to-work distance	⅛ to ¼ in.
Power supply	Special rectifier and control unit for 0.1-to-17-amp output, 100% duty cycle
Welding current	17 amp, dcsp
Welding speed	3 to 4 ipm
Production per 8-hr shift	12 to 16 housings

(a) For touch-up and repair, a bare low-carbon steel rod was used.

Fig. 18. Relay housing that was plasma-arc welded, and the joints used (Example 145)

Example 144. Change From Gas Tungsten-Arc Welding to Automatic Plasma-Arc Welding To Join Terminals on a Computer Memory-Grid Array (Fig. 17)

A computer memory-grid array was constructed of 18 plastic frames. Terminals on the outer sides of the stacked frames were welded to join the several layers, as shown in Fig. 17. The terminals were 0.010-in.-thick strips of 0.004-in.-thick copper, coated on both sides with 0.003 in. of BCuP-5 brazing alloy. Originally, the joints were welded by the gas tungsten-arc process, using a small hand-held torch. Because 1122 welds had to be made on each of the four sides of the array, manual gas tungsten-arc welding was too slow. Furthermore, weld spatter caused short circuits and high-resistance leaks, which altered the functioning of the array.

A change was made to automatic low-current plasma-arc welding. Before welding, the frames were clamped together and a copper grounding plate was placed over the joints, as shown. The terminals extended through holes in the grounding plate and projected 0.020 in. beyond. In addition to being an electrical ground, the grounding plate served as a fixture for holding the joints, as a heat shield to protect the plastic frames, and as a heat sink to conduct heat away from the terminals after the weld was made. The assembled array was placed in a traversing mechanism that passed each row of joints under the plasma-arc torch and, at the end of each row, indexed to the next row. The machine shut down automatically when the last row of joints on a side had been welded.

At each end of the grounding plate was a type 302 stainless steel arc-starting plate, where the arc was struck. The arc-starting plates burned through and warped quickly and had to be replaced frequently.

Automatic plasma-arc welding reduced welding time for an array from 7 hr to 30 min. On the average, only two joints in each array had to be repair welded. (An array contained about 4500 joints.) Actual arc time for one side was 2½ min. Welding details are given in the table that accompanies Fig. 17.

Example 145. Selection of Plasma-Arc Welding for Assembling Relay Housings (Fig. 18)

Housings for power relays used in aircraft and missiles were plasma-arc welded after consideration of soldering, brazing, gas tungsten-arc welding, and electron-beam welding. Soldering and brazing were eliminated because welding was more convenient, less expensive, and produced better joints. Electron-beam welding was ruled out because of the high cost of equipment, the welder skill required, and the effect of the vacuum on various electrical components. Equipment was available for plasma-arc welding, and its operation required less welder skill than gas tungsten-arc welding.

Housings were required to be hermetically sealed. Each housing was made of four components — a cover, a two-piece shell, and a base, as shown in Fig. 18. The base was a 1% silicon steel casting; the other components were press formed 1018 steel. The formed parts were 0.032 in. thick, and the joint areas of the cast base were also 0.032 in. thick.

Joints (Fig. 18) were designed for ease of assembly and to permit deposition of small edge-seal welds. In addition, this type of joint simplified repair welding.

After joint edges were degreased and wire brushed, the components were first assembled in a special tack welding fixture, a reasonable allowance being made for some mismatch. Tack welds were placed on the sides, and at the four corners of the cover and the base. The workpiece was then removed from the tack welding fixture and

placed in a manually rotated welding fixture, with the vertical axis turned to the horizontal. The piece was held by power-arm-actuated holding clamps. Next, a two-piece band of 1-by-⅜-in. copper was fitted around the shell and fastened with a garter spring, to serve as a heat sink to protect glass seals on terminal studs and connector pins. The straight sides and then the cover were manually welded in a single pass, using the settings and conditions given in the table that accompanies Fig. 18. Mismatch was adjusted (where needed) by melting down the protruding edge. The unit was allowed to cool to room temperature, and then the shell was welded to the cast base.

The plasma-arc torch operated continuously — in the pilot-arc (nontransferred) mode when not welding and in the transferred-arc mode when welding. Filler metal was required only for touch-up or repair, and then a bare low-carbon steel rod was used. Because the power arm attached to the fixture permitted the workpiece to be turned as needed, all welding could be done in the flat position. During welding, the assembly was purged with helium at a rate of 3 to 5 cu ft per hour.

Completed welds were inspected visually for pinholes, which were ground out and repaired. The units were given a preliminary leak test by pressurizing them with helium at 15 psi and observing bubble emission when units were immersed in the testing solution. Leaking joints were repair welded. Finally, the units were tested by mass spectrometer to make sure that the leak rate was less than 1.4×10^{-5} cu cm per second per cubic inch of sealed volume. Less than 1% of the relays were rejected in this final inspection.

The presence of 1% silicon in the cast steel presented no problem in maintaining weld quality.

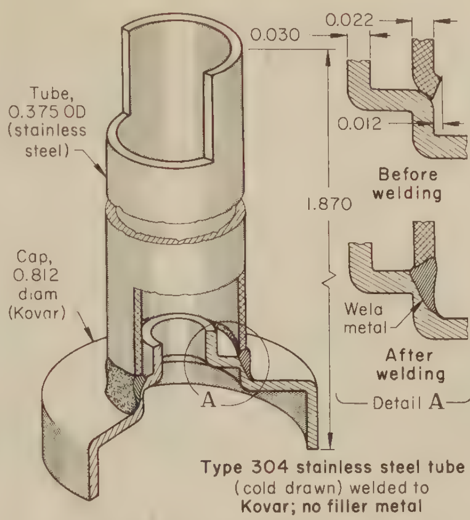
Example 146. Change From Oxyacetylene Welding to Plasma-Arc Welding for Joining Stainless Steel to Kovar (Fig. 19)

A circumferential weld was required to join a type 304 stainless steel tube to a Kovar electrode cap of a relay component, as shown in Fig. 19. [Kovar, an alloy with 29% Ni, 17% Co, 0.2% Mn, remainder iron, is used for making glass-to-metal seals because its coefficient of expansion is the same as that of certain types of glass.] The chief requirements of the welded joint were: (*a*) medium joint penetration, (*b*) smooth appearance, (*c*) carbon-free surface, (*d*) strength equal to that of the tube wall, and (*e*) resistance to penetration of mercury at 80 psi.

Originally, oxyacetylene welding (without filler metal) was used for making the weldment, the procedure employed being as follows: Prior to welding, both components were annealed in a hydrogen atmosphere. The tube and cap were clamped in a special jig to maintain alignment. The assembly was mounted, axis vertical, on a turntable, and welding was done in a single pass, using a hand-held torch. From 80 to 90 pieces were produced per hour, but welds were of poor quality, over 50% being rejected for carbon deposits and poor bonding and spreading of metal at the interface between the two components. [When the oxyacetylene welding process was used, the tube ends were not flared, as they were when plasma-arc welding was adopted (shown in the "Before welding" view in detail A, Fig. 19).]

Other joining processes, including brazing and gas tungsten-arc welding, were investigated. Brazing was unsatisfactory because it introduced metals into the joint that were attacked by mercury. Gas tungsten-arc welding was rejected because of the danger of contamination of the weld by the tungsten electrode.

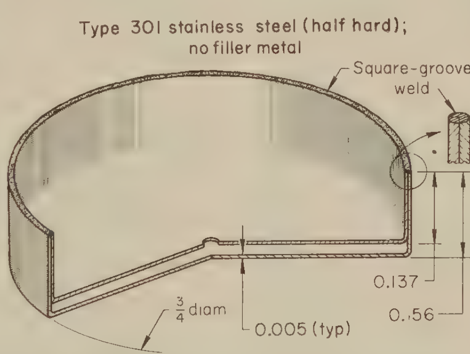
The problems were solved by changing to low-current plasma-arc welding. Details of the welding procedure are given in the table that accompanies Fig. 19. The prewelding treatment was the same as described above for oxyacetylene welding. No changes in fixturing were required, but joint design was slightly modified by flaring the tubes as shown in Fig. 19. With plasma-arc welding, production averaged 60 pieces per hour, but the rejection rate dropped to 0.05%, which more than compensated for the lower production rate.



Conditions for Plasma-Arc Welding

Joint type	Edge
Weld type	Corner-flange
Fixtures	Clamping jig; rotating positioner
Welding position	Horizontal (see figure)
Number of passes	One
Torch	10 amp, water cooled
Electrode	$\frac{3}{64}$-in.-diam EWTh-2
Filler metal	None
Orifice gas	Argon, at 0.6 cfh
Shielding gas	85% A – 15% H_2, at 18 cfh
Orifice-to-work distance	¼ in.
Power supply	0.1-to-10-amp, 60-to-80-v rectifier
Current	9 amp, dcsp
Voltage	70 v
Welding speed	6 rpm
Production rate	60 assemblies per hour

Fig. 19. Relay component that was plasma-arc welded, requiring fusion of type 304 stainless steel to Kovar. Joint design and weld are shown at right. (Example 146)



Conditions for Automatic Plasma-Arc Welding

Joint type	Edge
Weld type	Square-groove
Fixtures	Clamping jigs; rotating table; torch mount
Welding position	Flat
Torch	Machine held, water cooled
Electrode	0.020-in.-diam EWTh-2
Filler metal	None
Orifice gas	Argon, at 0.6 cfh
Shielding gas	97.5% A – 2.5% H_2, at 14 cfh
Orifice-to-work distance	0.050 in.
Power supply	10-amp, single-phase rectifier
Current	3.5 amp, dcsp
Welding speed	28 ipm
Annual production	5 million cups

Fig. 20. Double-wall cup that was sealed by plasma-arc welding to reduce rejection rate (Example 147)

Example 147. Change to Plasma-Arc Welding From Resistance Seam Welding To Decrease Rejections (Fig. 20)

Rejection rate for the small thin-wall double cup shown in Fig. 20 was about 4.5% when resistance seam welding was used to make the seal weld. The major requirement was that the press-fit-and-welded joint between the two 0.005-in.-wall cups be pressure-tight under a test applied at a later stage of assembly. Rejections were a significant cost factor because about five million parts were produced per year.

By changing to automatic low-current plasma-arc welding, welding time was increased threefold, but rejections were reduced to less than 1%.

Automation for plasma-arc welding was accomplished by installing two welding stations, each provided with clamping jigs for holding parts in position and rotating them under the torch. The torch was rigidly mounted on sliding ways so that it could be positioned accurately over the edge joint of an assembly at either station. A cup assembly was loaded on the fixture at one welding station, and rotation and the arc were initiated by a push button. While this assembly was being welded, another was being loaded on the second fixture. After the first cup had been welded, the torch was moved to the other welding station, and the second cup was welded.

Welding details are given in the table that accompanies Fig. 20. The completed welds were examined at a magnification of eight diameters. After further assembly, the finished unit was pressure tested with low-pressure, clean, dry air while immersed in water for 10 sec.

Welding Stainless Steel Foil

At very low currents, plasma-arc welding can be used for joining stainless steel foils (0.001 to 0.005 in. thick). For this work, a system such as that shown in Fig. 4 is used.

The following current settings (dcsp) and welding speeds have been satisfactory for welding three different thicknesses of stainless steel foil, using argon plus 1% hydrogen at 0.5 cfh through a 0.030-in.-diam orifice and at 20 cfh for shielding:

0.001-in. foil	0.3 amp, 5 ipm
0.003-in. foil	1.6 amp, 6 ipm
0.005-in. foil	2.4 amp, 5 ipm

Only edge-flange welds for butt joints are recommended for welding foil, and precise fixturing is a primary requirement. Figure 21 shows a typical fixturing arrangement for making the edge-flange weld. An essential part of any fixture used is a backing groove at least ¼ in. deep, because the underside of the joint must be shielded with gas during welding. The width of the backing groove is not critical; a range of $10t$ to $24t$ (t being the foil thickness) is satisfactory. Also, considerable tolerance is allowed on spacing between hold-down clamps; it can range from $15t$ to $30t$ (Fig. 21).

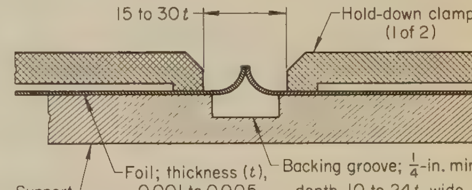


Fig. 21. Edge-flange joint, and design and dimensions of fixturing, for plasma-arc welding of stainless steel foil

Recommended Proportions of Grooves for Arc Welding (AWS)*

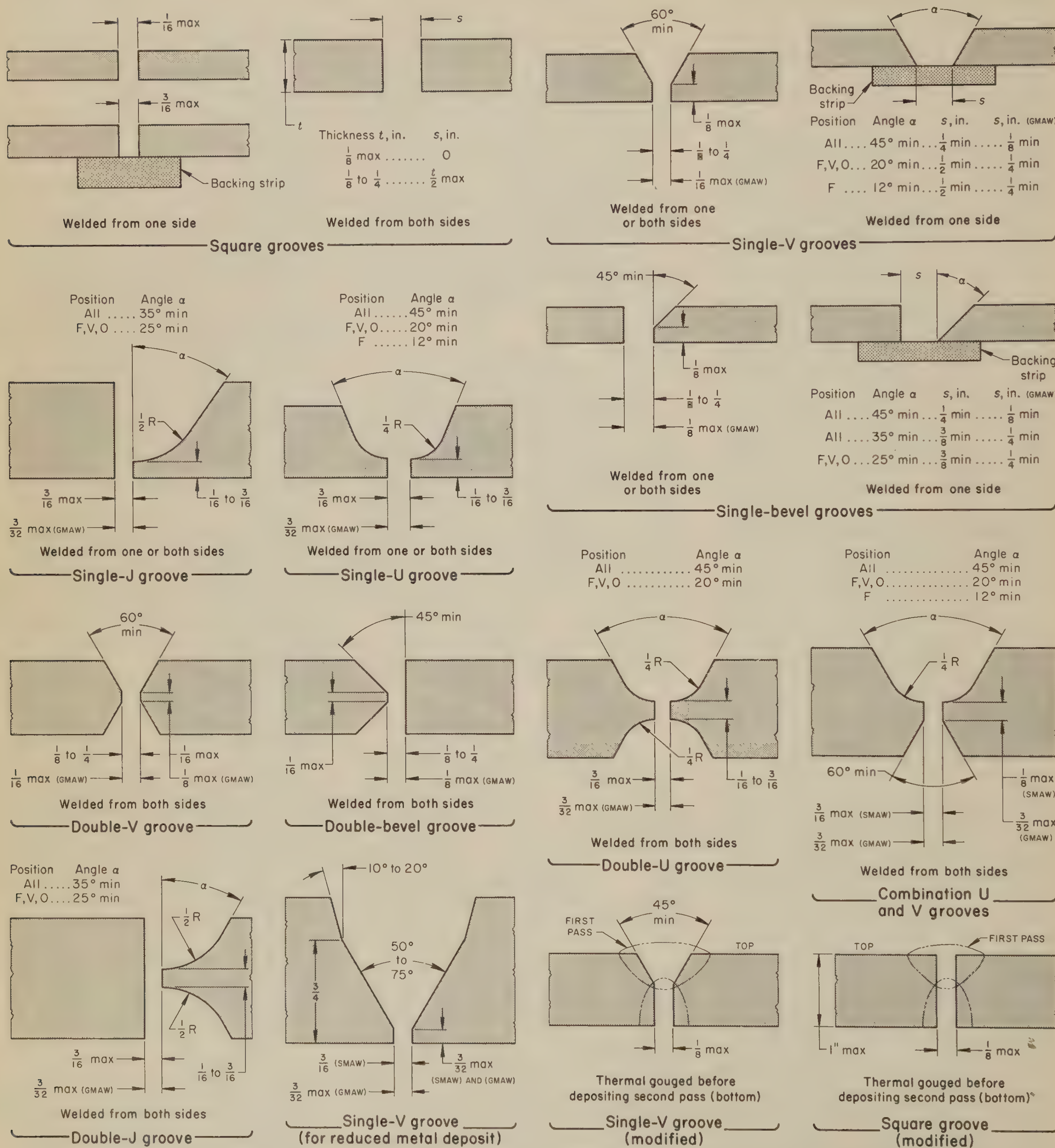


Fig. 1. Recommended proportions of grooves for butt joints made by shielded metal-arc, gas metal-arc, gas tungsten-arc, flux-cored arc and gas welding (except pressure gas welding). Dimensions that apply to gas metal-arc welding only are noted.

*Reproduced by permission from Welding Handbook, Sixth Edition, Section 1, American Welding Society, 1968, pages 8.3 through 8.8. For discussion on joint design, see Chapter 8, Section 1 of the Welding Handbook.

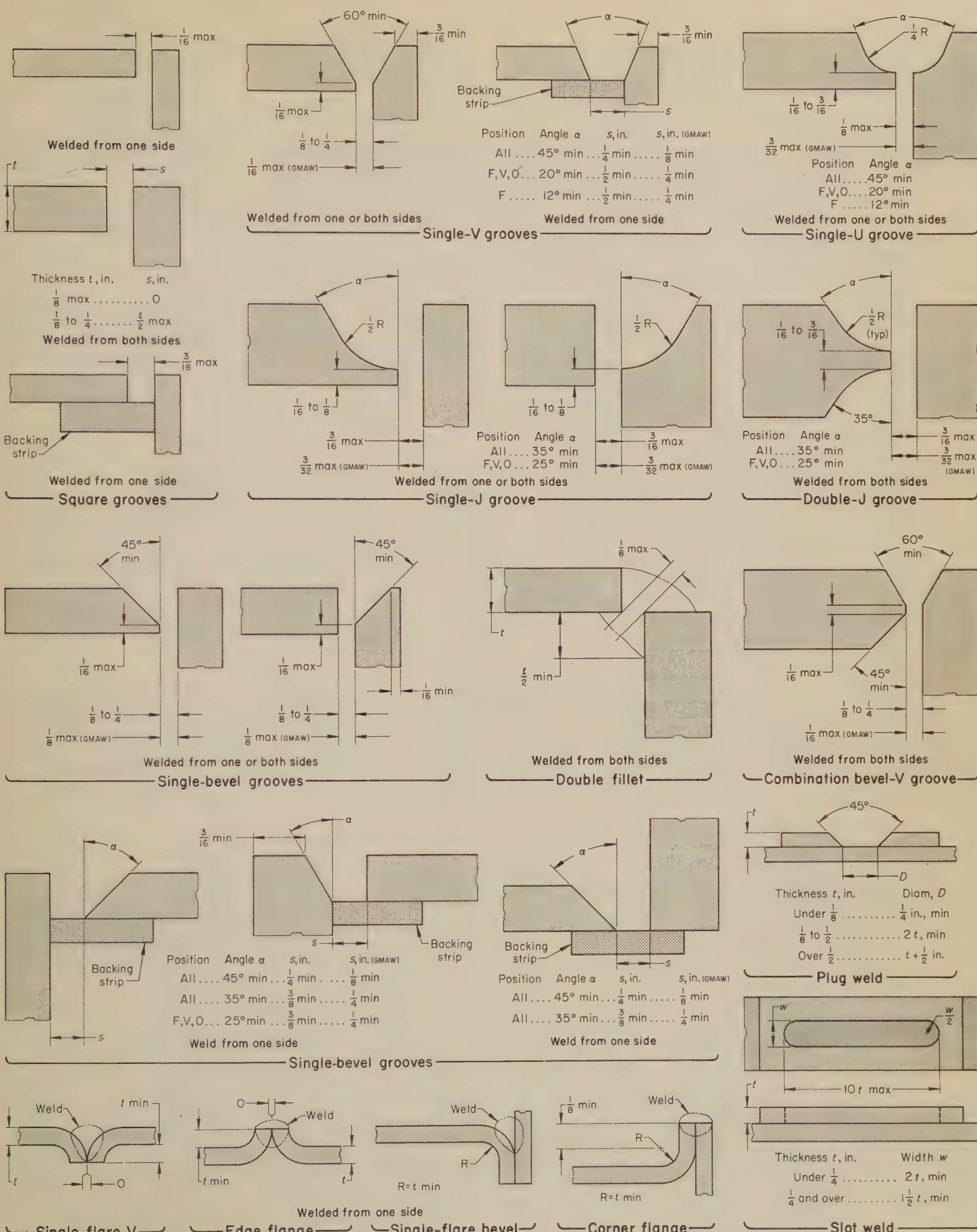


Fig. 2. Recommended proportions of grooves for corner and flange joints and plug welds made by shielded metal-arc, gas metal-arc, gas tungsten-arc, flux-cored arc and gas welding (except pressure gas welding). Dimensions that apply to gas metal-arc welding only are noted.

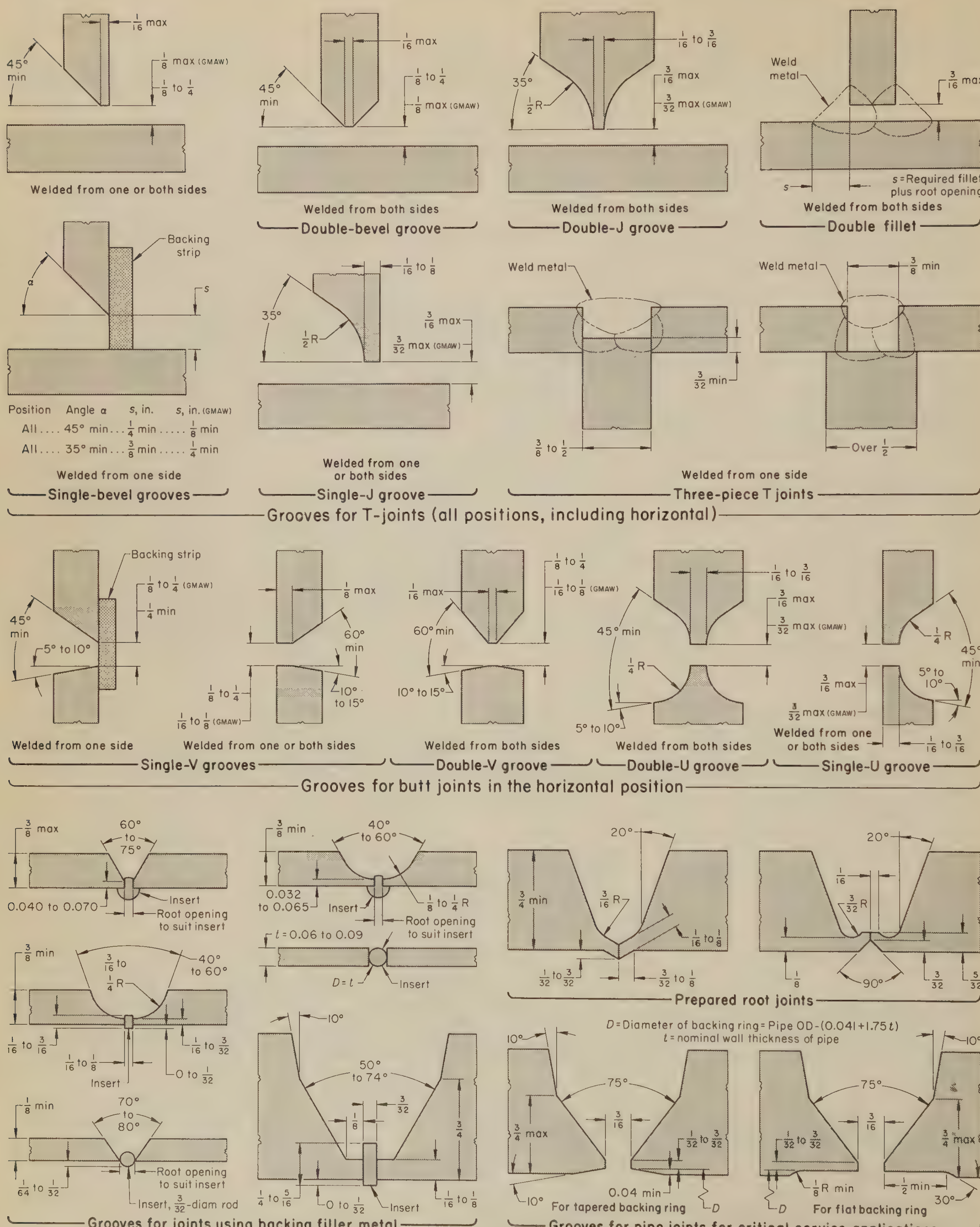


Fig. 3. Recommended proportions of grooves for T-joints and joints for specific applications made by shielded metal-arc, gas metal-arc, gas tungsten-arc, flux-cored arc and gas welding (except pressure gas welding). Dimensions for specific welding processes are noted.

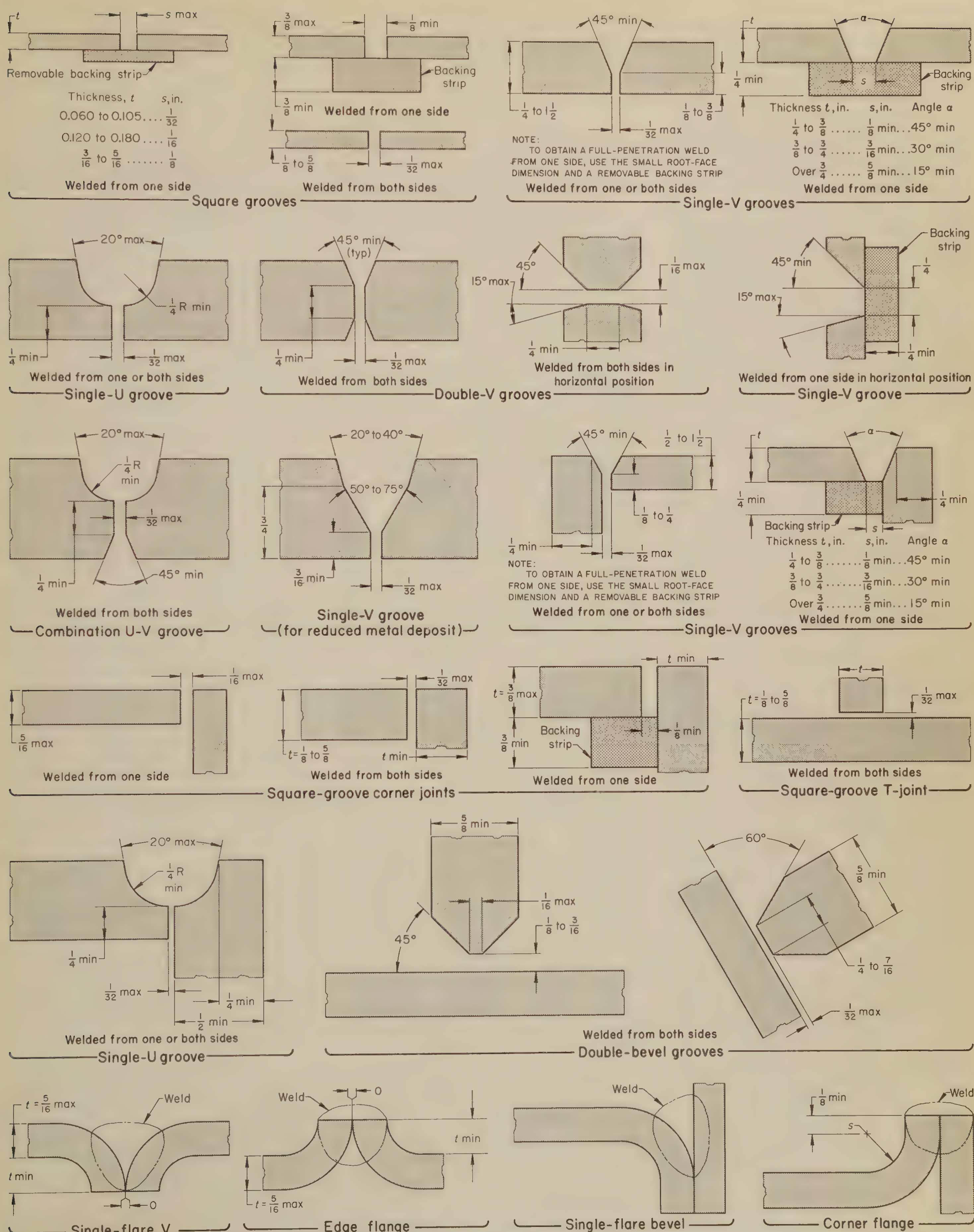


Fig. 4. Recommended proportions of grooves for joints made by submerged-arc welding

Hard Facing by Arc Welding

*By the ASM Committee on Hard Facing**

HARD FACING is the process of applying, by welding, a layer, edge or point of wear-resistant metal onto a metal part to increase its resistance to abrasion, erosion, galling, hammering or other form of wear. This article deals with the use of arc welding for this purpose. Hard facing by oxyacetylene welding is described in the article that begins on page 587 in this volume.

Hard facing may be applied to new parts to improve their resistance to wear during service, or to worn parts for the purpose of restoring them to serviceable condition. It is frequently used in applications where systematic lubrication against abrasion is not feasible or is inadequate to give the desired service life. In general, the wear-resistant coating is applied only to those critical surfaces of components where wear is maximum. Worn parts can be satisfactorily refaced or rebuilt many times before their replacement becomes mandatory.

The economic success of the process often depends on selective application of relatively expensive hard facing alloys to comparatively inexpensive base metals. Heavy or bulky parts that are difficult and costly to move can often be repaired or rebuilt in the field or in the plant where they are installed, by welding with portable equipment.

Hard Facing Alloys

Most hard facing alloys are marketed as proprietary materials. They are classified here in five major groups (1 to 5), primarily according to total alloy content (elements other than iron), with subdivisions based on the major alloying elements (see Table 1). Table 2 gives typical compositions of specific alloys in each subgroup. Usually both the wear resistance and cost increase as the group number increases. Table 2 in this article is a revised and expanded version of Table 2 in the article on Selection of Hard Facing Alloys, page 821 of Volume 1 of this Handbook. Choice of the form and type of alloy depends on the application and the welding process to be used.

Forms. Alloys for hard facing are usually available as bare cast or tubular rod, covered solid or tubular electrodes, or solid wire, and powder. The availability of a particular alloy in a given form depends on the ability of the alloy to be cast, shaped into wire or tubing, or produced in powder form. Alloys that do not lend themselves to economical production by any of these methods are usually inserted in granular form into a low-carbon steel tube during the process of roll forming the tube from strip. The continuous tube can be cut to rod lengths for "stick" electrodes or it can be coiled for use as electrode wire in semiautomatic or automatic welding.

Many alloys are available in more than one form. The bare cast and bare tubular rod forms are used in gas tungsten-arc welding, covered electrodes in shielded metal-arc welding, solid wire in gas metal-arc or submerged-arc welding, tubular (alloy-cored) wire in open-arc welding, and powder in plasma-arc welding.

Alloy Composition. The alloys in group 1A (see Table 2) are low-alloy steels that, with few exceptions, contain chromium as the principal alloying element. The total alloy content (including carbon) is between 2 and 6%. These are often used as buildup materials for support of harder, more highly alloyed hard facing alloys.

The alloys in groups 1B1 and 1B2 are similar to those in group 1A except that they contain a higher total alloy content (6 to 12%), and in group 1B2, carbon content is 2% or more. Many tool steels are included in this group. Group 1B2 includes several alloy cast irons.

Alloys of group 1 have the greatest shock resistance of all hard facing alloys except the austenitic manganese steels (groups 2C and 2D), and have better wear resistance than low-carbon or medium-carbon steel, which is the base metal to which they are usually applied. These alloys are less expensive than the other hard facing alloys, and are extensively used where machinability is necessary and only moderate improvement over the wear properties of the base metal is required.

The alloys in groups 2A1 and 2A2 are chromium-containing alloys with total alloy content of 12 to 25%. Many of these alloys have an appreciable content of molybdenum. The alloys with carbon content of 1.75% or more are shown in group 2A2; they are medium-alloy cast irons.

Molybdenum is the principal alloying element in nearly all group 2B alloys, most of which also contain appreciable amounts of chromium. These and the group 2C steels have total alloy content between 12 and 25%.

Group 2C alloys are austenitic manganese steels. Although manganese content predominates, the alloys contain appreciable amounts of nickel or molybdenum as an austenite stabilizer.

The hard facing alloys of groups 2A1, 2A2 and 2B are more wear resistant, less shock resistant, and more expensive than those in group 1. Groups 2C and 2D are highly shock resistant, but have limited wear resistance unless subjected to work hardening. Group 2D alloys have total alloy content of 30 to 37%, and carbon content ranging from less than 0.10% to more than 1.0%.

Group 3 alloys have total alloy content from 25 to 50%. They are high-chromium alloys, many of which contain nickel or molybdenum, or both. Carbon content ranges from about 1.75% to more than 5%. Group 3B alloys contain appreciable amounts of molybdenum and chromium, and group 3C, of cobalt and chromium. Groups 3A, 3B and 3C alloys are characterized by massive hypereutectic alloy carbides that impart wear resistance and some degree of resistance to corrosion and heat. They are more expensive than the alloys in groups 1 and 2.

Cobalt-base and nickel-base alloys with total content of nonferrous metals from 50 to 99% are classified in group 4. The cobalt-base alloys (group 4A) are generally rated as the most versatile of the hard facing materials. They resist heat, abrasion, corrosion, impact, galling, oxidation, thermal shock, erosion, and metal-to-metal wear. Some of these alloys retain useful hardness up to 1500 F and resist oxidation temperatures up to 2000 F. The nickel-base alloys (group 4B) are most effective for service involving both corrosion and wear. They are superior to the other hard facing alloys where wear is caused by metal-to-metal contact, as in bearings. They retain useful hardness up to about 1200 F and resist oxidation at temperatures up to 1600 F.

Group 5 alloys (not listed in Table 2) consist of hard granules of tungsten carbide distributed in a metal matrix. Various matrix metals are employed, including iron, carbon steel, nickel-base alloy, cobalt-base alloy, and bronze. The tungsten carbide materials provide maximum abrasion resistance under service conditions involving low or moderate impact.

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Some of the examples in this article were contributed by members of other Metals Handbook welding committees. Additional examples of surfacing that appear in this volume are recorded in Table 5, page 166.

Alloy Selection. For guidance in the selection of hard facing materials for specific applications, see the article on Selection of Hard Facing Alloys, on pages 820 to 833, in Volume 1 of this Handbook.

Selection of Welding Process

For a given hard facing application, the selection of the most suitable welding process and the welding technique to be used may be as important as the selection of the alloy. Along with service requirements, the physical characteristics of the workpiece, the metallurgical properties of the base metal, the form and composition of the hard facing alloy, the property and quality requirements of the weld deposit, the skill of the welder, and the cost of the operation must be considered in selecting an arc welding process. Discussion of these factors and their influence follows. Discussion of the individual processes appears on pages 156 to 160.

Workpiece Factors. The size, shape and weight of the workpiece always influence welding process selection. Very large, heavy parts that require hard facing or buildup coatings, and that are difficult or impossible to transport, usually require selection of an arc welding process for which the equipment can be readily moved to the site of the workpiece. In such applications, welding is most likely to be manual or semiautomatic, particularly when hard facing of relatively inaccessible areas is involved. In contrast, parts that can be conveyed readily to the welding equipment and that are to be processed in large quantities can be hard faced most effectively and economically by machine or automatic methods. Shielded metal-arc and open-arc welding, for which portable equipment is readily available, lend themselves to field applications, whereas submerged-arc, gas tungsten-arc, gas metal-arc, and plasma-arc welding are better suited to in-plant applications.

Properties of Base Metal. The chemical composition, melting temperature range, and expansion and contraction characteristics are the principal attributes of the base metal that influence selection of a welding process. The susceptibility of the base metal to thermal cracking, oxidation, or contamination at elevated temperatures also may need to be considered. Thus, when rapid heating could cause thermal cracking of the base metal, adequate preheat and a welding process that provides a moderate heating rate, preferably without sacrifice in efficiency, should be selected. In addition, the cooling rate from the welding temperature may have to be controlled, and residual stresses may have to be reduced by postweld stress relieving.

Form and Composition of Hard Facing Alloy. The physical and metallurgical properties of the hard facing alloy determine the forms in which it is available. Some of the harder, more brittle alloys cannot be produced in the form of drawn wire, and therefore they are produced as mixtures of powder and are inserted in a carbon steel tubular wire if they are to be used in gas metal-arc welding, open-arc welding, or submerged-arc welding, which require a continuous electrode wire. A variety of forms, such as wire, bare cast rod, or bare tubular rod, can be used as filler metal in gas tungsten-arc welding. Compositions of hard facing alloys are given in Table 2.

Table 1. Classification of Hard Facing Materials by Alloy Groups

Group	Total alloy content, %	Principal alloying elements
Low-Alloy Ferrous Materials		
1A	2 to 6	Cr, Mo, Mn
1B	6 to 12	Cr, Mo, Mn
High-Alloy Ferrous Materials		
2A	12 to 25	Cr, Mo
2B	12 to 25	Mo, Cr
2C	12 to 25	Mn, Ni
2D	30 to 37	Mn, Cr, Ni
3A	25 to 50	Cr, Ni, Mo
3B	25 to 50	Cr, Mo
3C	25 to 50	Co, Cr
Nickel-Base and Cobalt-Base Alloys		
4A	50 to 100	Co, Cr, W
4B	50 to 100	Ni, Cr, B
4C	50 to 100	Cr, Ni, Co
Tungsten Carbide		
5	75 to 96	WC in metal matrix

Properties and Quality Requirements of the Deposit. The properties and quality of hard facing deposits depend primarily on the hard facing alloy. Other influential factors are the base-metal composition, the welding process and method employed, the number of layers deposited, and other welding characteristics. The extent of base-metal "dilution" of the hard faced surface during welding will vary with the process and the number of layers. Dilution is the interalloying of the hard facing alloy and the base metal, and is usually expressed as the percentage of base metal in the hard facing deposit. A dilution of 10% means that the deposit contains 10% base metal and 90% hard facing alloy. As dilution increases, the hardness, wear resistance, and other desirable properties of the alloy deposit are reduced. Sometimes, in order to control composition, a buffer layer of weld metal is deposited between the base metal and the hard facing alloy. In addition to minimizing dilution, a buffer layer is often used to counteract the adverse effects of differences in coefficient of expansion-contraction between the hard facing alloy and the base metal.

One criterion for selection of a welding process should be the ability of the process to limit dilution while achieving a high deposition rate, and thus to avoid the necessity for a deposit thickness greater than that required for service. Typical dilution percentages, deposition rates, and minimum deposit thicknesses for different welding processes and various forms, compositions and modes of application of hard facing alloys are given in Table 3.

As shown in Table 3, dilution may vary from 1 to 60%, and the minimum practical deposit thickness of a single layer of hard facing alloy ranges from $\frac{1}{32}$ to $\frac{3}{16}$ in., depending on the welding process and the mode of application of the hard facing alloy. On parts where several layers have to be applied, deposits may be built up to an inch or more in thickness. For these parts, care must be taken in selecting the hard facing alloy, because very highly alloyed deposits are likely to spall if applied in thicknesses of more than $\frac{1}{4}$ in. When deposits less than $\frac{1}{32}$ in. thick are required, an alternative process, such as metal spraying, is usually more efficient than any welding process.

Welder Skill. It is essential to relate the quality requirements of the deposit to both the welding process and welder skill. For example, although manual gas tungsten-arc welding can be used to obtain high-quality deposits on relatively small areas, and in grooves and recesses, and although thin layers can be deposited with dilution as low as 10%, relatively high welder skill and close control of the welding operation are necessary. In contrast, automatic submerged-arc welding requires a minimum of welder skill and results in high deposition rates, but penetration is deep, dilution is greater, and consequently it may be necessary to make use of a buffer layer or to deposit two or more layers of the hard facing alloy to obtain the full properties of the alloy.

In general, earthmoving and mining equipment can be hard faced adequately in the field by relatively unskilled welders. Selection of process is usually based on maximum deposition rate, and high dilution rates will seldom significantly affect the suitability of the coating for service. Hard facing of valves, on the other hand, requires highly skilled welders and precise control of the welding operation, and is frequently automated. Excessive dilution or contamination of the deposit can result in failure of the part during service.

Cost. Depending on their form and composition, hard facing alloys cost from about 50¢ to more than $11 per pound. Equipment and operating costs for appropriate welding processes also vary considerably. These differences are discussed in the sections dealing with specific processes and in some of the production examples.

Relating Selection Factors. At least three selection factors must be coordinated — namely, the base metal, the composition and form of the hard facing alloy, and the welding process.

Many components used in mining and quarrying machinery are large and rugged, and by following a few simple rules for hard facing, satisfactory service can be obtained. Dimensional limits are relatively broad and metallurgical quality is seldom critical. Consequently, acceptable hard facing of these components is likely to involve only the minimum number of selection factors, as in the following examples.

Examples 148 to 151. Selection of Alloy and Welding Process for Hard Facing Components of Mining and Quarrying Equipment

Example 148 — Rock-Crusher Rolls. These rolls, usually made of austenitic manganese steel, were hard faced to reduce the rate of over-all wear and to ensure an even wear pattern across the working face. Typically, a roll was surfaced with both buildup and hard facing layers.

Alloy selection for the buildup layer depended primarily on the base metal. A group 2C alloy (austenitic manganese steel) was suitable for austenitic manganese steel

rolls, and a group 1A alloy, for low-alloy steel rolls. Following buildup, a group 3 alloy was deposited, using transverse beads, two layers thick, on the area subjected to the most severe wear — the center two-thirds of the roll face. The outer portions of the roll face were surfaced with a group 2A alloy.

Hard facing was done by shielded metal-arc welding or semiautomatic open-arc welding. A typical austenitic manganese steel roll with a diameter of 36 in. and a face width of 18 in. required about 200 to 250 lb of deposited metal for buildup and hard facing.

Example 149 — Pug-Mill Knives. These knives, usually made of hardenable carbon steel, were selectively hard faced with a group 5 alloy (tungsten carbide) to resist severe abrasive wear and to maintain a sharp cutting edge. The leading face and edge of a knife were the critical locations for wear. The hard facing alloy was commonly applied by manual shielded metal-arc or oxyacetylene welding. Other knives made of cast iron were preheated to 1200 F, this temperature was held during welding, and knives were cooled slowly.

Example 150 — Traction Wheels. Wheels for mine cars, skips, cranes and other mobile equipment were hard faced to improve their wear resistance. A typical flanged wheel made of carbon steel (0.30 to 0.40% C) was hard faced with a group 1B alloy. The part was given a soaking preheat of 300 to 400 F before welding. The coating was applied by shielded metal-arc welding or by automatic submerged-arc welding, depending on the number of wheels to be processed. After hard facing, the wheels were cooled slowly to avoid cracking the overlay and to improve machinability, and they were then turned to finish dimensions.

Example 151 — Screen-Deck Sections. Cast austenitic manganese steel screen-deck sections, used in heavy-duty rock-screening equipment, were hard faced with a group 3A alloy to extend their service life. A continuous, two-pass layer was deposited, using semiautomatic open-arc welding. Hard facing normally resulted in a 75% improvement in the life of the screens.

Table 2. Typical Compositions of Hard Facing Alloys

C	Mn	Si	Cr	Ni	Mo	W	V	Co	B	Others	Total
					Group 1A						
0.15	0.90	0.50	0.50	...	0.30	...	...	...	...	...	2.35
0.23	0.90	0.50	0.40	1.00	0.60	...	...	...	...	...	3.63
0.50	0.80	0.30	1.00	...	...	...	0.20	...	...	...	2.80
0.10	0.80	0.30	1.50	...	...	...	...	...	...	...	2.70
0.15	1.50	0.80	2.50	...	...	...	...	...	...	...	4.95
0.35	1.90	0.20	3.00	...	...	...	...	...	...	...	5.45
0.63	1.30	0.80	2.40	...	...	...	...	...	...	...	5.13
0.10	1.20	0.80	2.10	...	1.00	...	...	...	...	...	5.20
0.15	1.10	0.70	3.00	...	0.90	...	...	...	...	...	5.85
0.25	1.10	0.70	2.00	...	1.00	...	...	...	...	...	5.05
0.55	1.10	0.50	2.50	...	0.40	...	0.60	...	...	...	5.65
					Group 1B1						
0.20	2.20	0.50	3.50	...	...	...	...	...	...	...	6.40
0.30	0.20	0.80	4.50	...	1.00	...	...	...	...	...	6.80
0.30	1.70	1.20	6.00	...	0.80	1.50	...	...	...	...	11.50
0.50	0.80	1.00	7.70	...	...	1.50	...	...	...	...	11.50
0.60	1.10	0.80	5.50	...	0.50	...	...	...	...	...	8.50
0.80	0.90	0.50	5.00	...	1.00	...	0.30	...	...	...	8.50
0.90	0.80	1.00	5.00	...	0.50	...	...	...	...	...	8.20
0.90	0.40	0.40	9.50	...	0.60	...	...	...	...	...	11.80
1.00	0.90	0.30	6.70	...	0.80	...	...	...	...	...	9.70
1.30	2.80	0.70	5.00	1.70	...	...	...	...	...	...	11.50
1.80	2.00	0.40	3.00	...	...	...	...	...	...	...	7.20
1.80	0.50	0.50	4.00	...	...	...	...	...	...	...	6.80
1.80	0.30	1.00	5.40	...	...	...	...	...	0.50	...	9.00
1.90	0.60	0.90	8.00	...	...	...	0.20	...	0.30	...	11.90
					Group 1B2						
2.00	0.80	0.70	7.00	...	0.30	...	...	...	...	...	10.80
3.00	0.70	1.00	3.10	3.00	...	...	...	...	...	...	10.80
3.50	0.50	0.50	2.00	...	5.00	...	...	...	...	...	11.50
					Group 2A1						
0.40	0.40	3.80	16.50	...	...	...	...	...	...	...	21.10
0.50	0.90	1.10	5.60	5.40	...	...	...	...	...	...	13.50
0.50	2.00	1.40	9.00	...	1.80	...	...	...	...	...	14.70
0.70	3.20	1.30	9.10	...	...	...	...	...	...	...	14.30
0.75	6.00	1.80	15.50	...	...	...	...	...	...	...	24.05
1.20	4.00	0.90	7.00	3.00	...	...	...	...	...	...	16.10
1.25	3.00	...	12.00	...	...	...	...	...	...	...	16.25
0.20	...	...	5.00	...	3.00	3.60	0.30	...	...	...	12.10
0.24	0.90	0.70	2.50	3.20	7.20	...	...	...	...	...	14.74
0.40	0.50	0.70	4.00	...	7.00	1.80	1.00	...	...	...	15.40
0.70	0.50	0.70	4.00	...	7.30	1.80	1.10	...	...	...	16.10
0.85	0.50	0.70	4.00	...	5.00	6.00	1.80	...	...	...	18.85
					Group 2A2						
1.75	0.30	1.00	9.40	...	...	...	0.20	...	...	...	12.65
2.00	0.60	1.50	9.00	...	...	...	0.20	...	0.88	...	14.18
2.50	1.00	0.70	8.10	...	...	...	...	...	...	...	12.30
2.75	1.40	1.00	16.00	...	1.00	...	...	...	...	...	22.15
3.00	0.80	1.80	6.50	...	...	...	...	...	...	...	12.10
3.00	2.00	1.00	14.00	...	1.00	...	...	...	...	...	21.00
3.50	1.50	1.50	16.00	...	1.00	...	...	...	...	...	23.50
4.00	1.00	0.90	6.00	...	4.20	...	...	...	...	...	16.10
					Group 2B						
0.80	...	...	4.00	...	9.00	...	1.50	...	...	...	15.30
1.00	...	...	0.90	...	15.30	...	...	...	...	...	17.20
1.40	...	...	4.10	...	9.70	...	...	...	1.40	...	16.60
2.60	...	...	4.70	...	5.60	...	...	...	...	...	12.90
3.60	...	...	4.50	...	8.20	...	2.40	...	1.00	...	19.70
3.75	1.00	1.00	...	...	10.00	...	...	...	...	...	15.75

Arc Welding Processes Used for Hard Facing

The arc welding processes capable of providing the fusion bond required in hard facing applications (listed in descending order of their use) are shielded metal-arc, submerged-arc, open-arc, gas metal-arc, gas tungsten-arc, and plasma-arc welding. Oxyacetylene welding is described in the article on Hard Facing by Oxyacetylene Welding, page 587, in this volume.

Oil-Refinery Applications. Several arc welding processes are used in hard facing components of catalytic-cracking equipment. Surfaces exposed to the action of the moving catalyst, which sometimes impinges at high velocity and at temperatures that may reach 1200 F, are subjected to severe erosion and abrasion. Hard facing of such surfaces eliminates the need to design

Table 3. Characteristics of Welding Processes Used in Hard Facing

Welding process	Mode of application	Form of hard facing alloy	Weld-metal dilution, %	Deposition, lb per hr	Minimum thickness, in.(a)	Applicable hard facing alloys
Oxyacetylene	Manual	Bare cast rod; tubular rod	1 to 10	1 to 6	1/32	All(b)
	Manual	Powder	1 to 10	1 to 15	1/32	All(b)
	Automatic	Extra-long bare cast rod; tubular wire	1 to 10	1 to 6	1/32	All(b)
Shielded metal-arc	Manual	Flux-covered cast rod; flux-covered tubular rod	15 to 25	1 to 6	1/8	All(b)
Open-arc	Semiautomatic	Alloy-cored tubular wire	15 to 25	5 to 25	1/8	Iron-base
	Automatic	Alloy-cored tubular wire	15 to 25	5 to 25	1/8	Iron-base
Gas tungsten-arc	Manual	Bare cast rod; tubular rod	10 to 20	1 to 8	3/32	All(b)
	Automatic	Various forms(c)	10 to 20	1 to 8	3/32	All(b)
Submerged-arc	Semiautomatic	Bare tubular wire	20 to 60	10 to 20	1/8	Iron-base
	Automatic, single wire	Bare tubular wire	30 to 60	10 to 25	1/8	Iron-base
	Automatic, multiwire	Bare tubular wire	15 to 25	25 to 60	3/16	Iron-base
	Automatic, series arc	Bare tubular wire	10 to 25	25 to 35	3/16	Iron-base
Plasma-arc	Automatic	Powder(d)	5 to 30	1 to 15	1/32	All(b)

(a) Recommended minimum thickness of deposit. (b) Iron-base, nickel-base, and cobalt-base alloys; tungsten carbide composites. (c) Bare tubular wire; extra-long (8-ft) bare cast rod; tungsten carbide powder with cast rod or bare tubular wire. (d) With or without tungsten carbide granules.

Table 2 (Continued)

C	Mn	Si	Cr	Ni	Mo	W	V	Co	B	Others	Total
Group 2C											
0.70	14.00	0.90	...	4.00	...	...	...	...	...	...	19.60
0.70	14.00	0.90	...	...	1.00	...	...	...	...	...	16.60
0.80	14.00	0.30	4.00	4.00	...	...	...	...	...	...	23.10
0.75	14.60	0.70	...	...	0.80	...	...	...	...	3.00 Cu	19.85
Group 2D											
0.07	7.50	0.60	18.50	4.00	...	...	...	...	...	...	30.67
0.40	14.00	0.50	14.50	1.00	1.70	...	0.60	...	...	...	32.70
0.50	4.50	0.60	20.00	10.00	1.40	...	...	...	...	...	37.00
0.80	...	...	22.00	9.00	0.50	...	...	...	...	...	32.30
1.20	14.00	0.80	15.00	1.00	...	...	...	...	...	...	32.00
Group 3A											
1.75	1.00	1.50	30.00	3.00	1.50	...	...	...	...	...	38.75
2.00	2.20	2.30	23.50	...	...	...	...	...	...	...	30.00
2.25	0.70	1.90	25.00	...	...	...	...	...	...	...	29.85
2.50	1.00	0.80	25.00	...	...	...	...	3.75	0.55	...	33.60
2.75	1.00	0.80	26.00	...	...	...	...	...	...	...	30.55
3.50	1.20	0.80	31.00	...	1.00	...	...	...	...	...	37.50
4.00	2.50	2.50	27.00	...	...	...	...	...	...	...	36.00
4.00	6.00	1.80	29.00	...	...	...	...	...	...	...	40.80
4.00	1.00	1.30	29.00	3.50	...	...	...	...	...	...	38.80
4.00	...	1.00	16.00	6.00	...	...	0.50	...	...	...	27.50
4.10	5.50	0.30	25.30	...	2.10	...	...	...	...	...	37.30
4.50	1.00	2.00	30.00	...	...	...	...	...	...	...	37.50
4.50	1.90	1.90	24.00	...	1.40	...	...	...	...	...	33.70
6.00	1.20	1.40	34.00	...	0.90	...	...	...	...	...	43.50
Group 3B											
3.10	0.30	1.20	17.00	...	16.00	...	1.90	...	...	...	39.50
3.90	...	...	32.00	...	6.00	...	...	...	...	...	41.90
4.10	...	...	16.00	2.00	8.00	...	1.00	...	...	...	31.10
4.30	...	...	16.00	6.00	8.00	...	...	...	...	1.00 Ti	35.30
4.40	2.50	1.70	29.00	...	4.00	...	0.20	...	...	...	41.80
5.80	0.50	1.50	22.00	...	6.00	4.00	...	...	...	...	39.80
Group 3C											
2.30	...	...	16.00	6.00	...	...	...	20.00	...	...	44.30
3.60	0.60	1.60	15.40	...	3.10	...	...	23.30	...	...	47.60
3.80	...	1.50	16.00	4.00	6.50	...	...	20.00	...	...	51.80
Group 4A											
0.25	0.80	0.80	27.00	2.75	5.00	...	...	Rem	...	1.50 Fe	...
1.10	...	...	26.25	...	...	4.20	...	Rem	...	7.00 Fe	...
1.35	0.80	1.50	29.00	2.50	0.80	8.00	...	Rem	...	2.50 Fe	...
2.45	0.80	1.50	30.00	2.50	0.80	12.50	...	Rem	...	2.50 Fe	...
2.80	0.80	1.50	30.00	2.50	0.80	12.50	...	Rem	...	2.50 Fe	...
2.50	0.80	1.50	32.00	2.50	0.80	17.00	...	Rem	...	2.50 Fe	...
3.25	0.80	1.50	26.00	2.50	0.80	14.00	...	Rem	...	4.00 Fe	...
0.07	0.80	2.50	21.00	1.50	0.80	4.50	...	Rem	2.40	1.50 Fe	...
Group 4B											
0.45	0.80	2.25	11.00	Rem	...	...	...	1.20	2.50	1.30 Fe	...
0.60	0.80	4.00	13.00	Rem	...	...	...	1.00	3.00	4.00 Fe	...
0.75	0.80	4.50	15.00	Rem	...	...	...	0.80	3.50	4.50 Fe	...
1.00	...	...	14.00	Rem	...	14.00	...	15.00	3.00	...	...
Group 4C											
0.09	0.80	0.80	16.00	Rem	17.00	4.50	...	...	...	5.00 Fe	...
0.20	0.80	0.80	21.00	Rem	...	...	...	...	...	...	...
1.40	0.80	0.80	25.00	Rem	10.00	10.00	...	10.00	...	12.50 Fe	...
2.00	0.80	0.80	26.00	Rem	...	8.70	...	0.50	...	3.00 Fe	...
2.35	0.80	1.00	29.00	Rem	...	15.00	...	10.00	...	5.00 Fe	...
1.75	0.80	1.20	25.00	22.00	...	12.00	...	Rem	...	2.50 Fe	...

heavy components with large thickness allowances to compensate for erosion in service.

For hard facing high-temperature refinery equipment, iron-base alloys containing 25 to 35% Cr, 3 to 5% C, and varying amounts of manganese, nickel or molybdenum (Group 3A), and cobalt-base alloys containing 25 to 35% Cr, 0.5 to 3% C, 3 to 14% W, and 1 to 3% Mo and Ni (Group 4A), have been found to be most successful. In general, for components subjected to temperatures up to 1000 F, the high-chromium iron-base alloys are used, and the cobalt-base alloys are preferred for components that are subjected to higher service temperatures, above 1000 F.

In the fluid-catalyst type of catalytic-cracking unit, the components that are normally hard faced include slide valves in lines carrying hot catalyst and in flue-gas lines, catalyst cyclone separators, deflector baffles in vessels and orifice chambers, and the catalyst-carrying lines.

A typical slide valve is usually made of a 5% Cr, 0.5% Mo steel. Because the temperature of the catalyst-containing stream often exceeds 1000 F, a cobalt-base hard facing alloy containing about 1% C is generally used. For more severe conditions, a cobalt-base alloy containing up to 3% C is sometimes used. Use of these alloys entails some sacrifice in ease of deposition and some increase in sensitivity to cracking of the deposit. To minimize sensitivity to cracking and required thickness of the overlay material, repair of eroded areas and buildup are accomplished with type 310 or 312 stainless steel prior to depositing a final and relatively thin layer of a hard facing alloy. A stainless steel coating is also applied to other surfaces that are directly exposed to high temperature but not to the action of the flowing catalyst.

Minimum thickness of the hard facing overlay on slide valves is about ⅛ in. Deposition is by shielded metal-arc welding, and when close dimensional tolerances are specified, the deposit is finish machined or ground. By hard facing, the operating life of slide valves is extended three to ten times, depending on the severity of service.

The surfaces of a catalyst cyclone separator are selectively coated with hard facing deposits of carbon steel, 5% Cr steel, and stainless steels 410 and 304, the selection of which depends on the conditions of wear in the separator. Depending on operating temperature, alloys of group 3A or 4A are deposited manually in areas subjected to high catalyst velocities and where it is not possible to apply abrasion-resistant refractory linings. Shielded metal-arc welding is done in the flat position whenever possible, using the shingle-overlap method to minimize dilution. Deposit thickness ranges from ⅛ to ¼ in.; after deposition, the surface is ground to a thickness no greater than 1⁄16 in. The hard facing deposits are stress relieved as required. As a result of hard facing, the service life of separator components is increased two to five times.

Among the various components of fluid catalytic-cracking units, the catalyst lift pipes account for the largest volume of hard facing alloy. These pipes range from 2 to 6 ft in diameter and are generally made of carbon steel, although the hotter portions of the pipe may be made of 5% Cr, 0.5% Mo steel. Some pipes contain slight bends, and the hot catalyst, moving at a velocity of 15 ft per second, causes extensive erosion in these regions unless they are protected by hard facing. Alloys of either group 3A or 4A are used for this purpose, depending on whether the operating temperature is below or above 1000 F.

Because large areas are surfaced, semiautomatic welding processes are preferred. Open-arc welding is most widely used; submerged-arc welding is also suitable. Welding is done in the flat position, using the weave-bead technique to provide a minimum buildup thickness of ⅛ in.

When depositing a high-carbon high-chromium iron-base alloy, the welding conditions are controlled so as to produce a pattern of fine hairline cracks perpendicular to the direction of the weld and of catalyst flow. The hairline-crack pattern and the brittle nature of the deposit prevent progression of cracks into the base metal, which might cause structural failure — such failures are likely to occur when a few widely scattered cracks are produced in the coating. To minimize distortion in piping, the coating is deposited by "quartering" — that is, with each bead covering 90° of the pipe circumference after the first bead has been deposited, the pipe is turned 180°, and then alternately through 90° and 180° until the overlay is completed.

Before joining sections of hard faced pipe by welding, the edges of the pipe are beveled by machining or grinding away the hard facing deposit, so as to prevent the pipe weld from being contaminated by the facing alloy. After the

weld joint is completed, hard facing is applied to it manually. The pipe is then stress relieved at 1000 F or higher, depending on the base metal.

The components of the moving-bed type of catalytic-cracking unit that are usually hard faced include lift pipes, downcomers, lift bells, wear plates, shrouds, and plug valves. These operate at 900 to 1200 F. Air-distributor cones, which operate at temperatures up to 1500 F, are also protected by hard facing alloys. Most of these components are well suited to hard facing by automatic open-arc welding. The hard facing alloys used are the same as those used for the fluid-catalyst units.

Hard Facing by Shielded Metal-Arc Welding

The equipment used for hard facing by shielded metal-arc welding is similar to that used for welding joints by shielded metal-arc welding, which is described in the article that begins on page 1 of this volume. Speed of travel, position of the electrode relative to the puddle, arc voltage, and amperage are modified to minimize penetration and the consequent dilution of the deposit. Depending on the surface area to be faced, the bead-deposit pattern may be of the stringer or weave type, with or without staggering of beads, as dictated by service requirements. Selection of the bead pattern and sequence depends also on the accessibility of the surface to be hard faced and the distortion limits of the workpiece. The width of weave should usually be no greater than 2½ times the diameter of the electrode.

Shielded metal-arc welding is used for manual surfacing of small or complex parts, and for maintenance and field repair, where welding must be done in all positions. The principal disadvantages of the process are the low deposition rates obtained and the resultant high labor costs per pound of alloy deposited.

Shielded metal-arc welding is used for hard facing the slide valves and cyclone separators of catalytic-cracking units, as noted in the previous section.

Coke-pusher shoes, which are used in the coke ovens of steel mills, are also hard faced by shielded metal-arc welding. In service, the shoes are supported by a ram and are used to push highly abrasive, hot coke out of the ovens into hopper cars for transfer to a quenching tower. In emptying an oven, the ram travels about 40 ft, making many such trips during each shift. The sole of the shoe is subjected to severe heat and abrasion as it rides over the pulverized hot coke and the brick oven floor. Hard facing of such shoes by shielded metal-arc welding is described in the following example.

Example 152. Hard Facing Coke-Pusher Shoes by Shielded Metal-Arc Welding (Fig. 1)

The base of a coke-pusher shoe sole made of low-carbon steel plate (about 10½ in. wide and 48 in. long) was hard faced manually, using covered electrodes of one of the higher-carbon alloys of groups 3A or 3B. The shoe was positioned to permit flat-position welding, and an overlay about ¼ in. thick was applied to the working surface

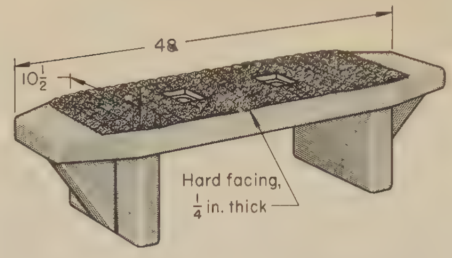
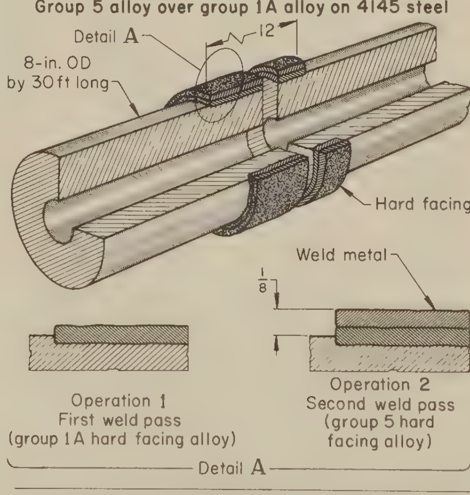


Fig. 1. Coke-pusher shoe with sole hard faced by shielded metal-arc welding (Example 152)

of the sole, as shown in Fig. 1. By properly slanting the shoe, the beads were stacked, so as to obtain a deposit consisting of a single thick layer with 4-in.-long beads running parallel to the direction of wear. Neither preheating nor postheating was employed. Transverse bead checking (cracking) was typical, but not detrimental. About 50 lb of hard facing alloy was required for a single shoe. The service life of pusher shoes hard faced with a group 3A or 3B alloy was 18 months, compared with a 3-month service life for shoes coated with less wear-resistant alloys.

Hard Facing by Submerged-Arc Welding

In general, the advantages of the submerged-arc process for hard facing are the same as for joint welding applications (see the article on Submerged-Arc Welding, page 46 in this volume). Weld-metal quality is consistently high, and the high current densities normally employed permit high deposition rates. Also, the high speed and deep penetration that are characteristic of the process make it



Conditions for Submerged-Arc Welding and Open-Arc Welding

Power supply	600-amp rectifier
Hard facing alloys	Group 1A; group 5(a)
Flux	Neutral, with group 1A alloy; none, with group 5 alloy
Current	400 to 450 amp
Voltage	35 v
Preheat and postheat	700 F
Travel speed	24 ipm
Surface finish	Rough, as welded
Depth of deposited metal	⅛ in. (total)

(a) First layer with group 1A alloy; second layer with group 5 alloy.

Fig. 2. Drill collar showing hard facing deposits made in two passes, using submerged-arc and open-arc welding (Example 153)

adaptable to some applications involving both buildup and facing. Other advantages include excellent appearance, improved working conditions, and more uniform quality resulting from the flux-covered arc, elimination of weld spatter, and the ease of removal of fused flux (slag) from the hard facing deposit after it cools.

Likewise, the major disadvantages of submerged-arc welding for hard facing are essentially the same as for joint welding applications. It is generally limited to hard facing of simple round or flat parts, and is not usually adaptable to field work. Also, because of the deep-penetration characteristic of submerged-arc welding, there is a high percentage of base-metal dilution (see Table 3) and a large buildup of heat in the workpiece. To obtain an undiluted surface deposit, two or three layers of hard facing alloy are sometimes needed. Also, submerged-arc welding is not readily applicable for hard facing components made of austenitic manganese steel, because the excessive heat buildup may prove detrimental and cause the alloy to become brittle.

Applications involving the use of submerged-arc welding for hard facing are discussed in the three examples that follow.

Example 153. Hard Facing of Oil-Field Drill Collars by Submerged-Arc and Open-Arc Welding (Fig. 2)

Steel drill collars, 30 ft long and 8 in. in outside diameter, and made of 4145 steel, were hard faced by submerged-arc and open-arc welding. Two layers of alloy were deposited around the collar, as shown in Fig. 2.

Before hard facing, collar surfaces were cleaned with a solvent to remove cutting fluids and rust preventives. The collar was then placed on a stand equipped with rollers and a power-driven three-jaw chuck that was capable of slowly rotating the collar during the hard facing operation. Using portable high-pressure gas burners, the collar was preheated to 700 F for a distance of 12 in. on either side of the area to be hard faced. The hard facing was done in two passes, the first by submerged-arc welding and the second by open-arc welding, using the conditions given in the table accompanying Fig. 2.

In the first pass, 9½ lb of a group 1A alloy was deposited, using a neutral flux; in the second pass, 4¾ lb of a group 5 alloy was deposited without any flux. The combined thickness of the deposits was about ⅛ in. The electrode was positioned ⅝ in. off-center, and a spiral motion of the welding head was used to obtain a stringer bead.

The unit cost of hard facing a drill collar of the above dimensions was about $54, and the cost of the welding unit was between $2000 and $2500.

Many carbon and low-alloy steel components used in such earthmoving equipment as crawler tractors, power shovels, and cranes, are rebuilt and hard faced with alloys of groups 1A and 1B.

In service, crawler tractors are ultimately rendered inoperative by deterioration of the undercarriage track system, caused by impact and excessive metal-to-metal wear. Track-system parts are not lubricated because lubricant and road sand form an abrasive slurry that accelerates wear. Track parts are operated dry until wear causes them to become loose and out-of-timing. Components are then rebuilt

by welding and hard faced, as in the following example.

Example 154. Hard Facing of Tractor Rollers and Idlers by Submerged-Arc Welding (Fig. 3)

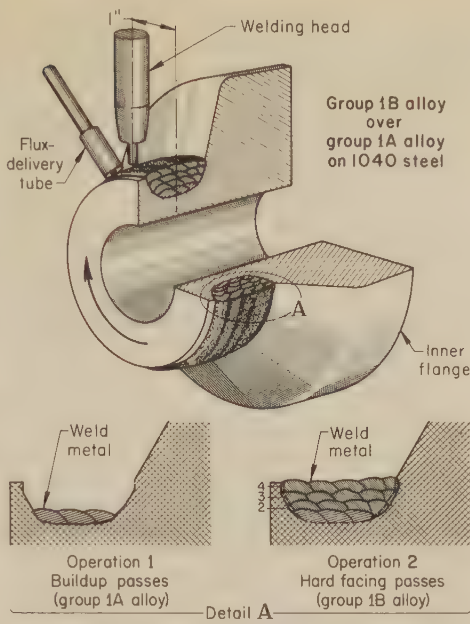
Using automatic submerged-arc welding, tractor rollers and idlers, ranging in size from 7 to 35 in. in outside diameter and from 4 to 11 in. in width, were welded with buildup and hard facing layers at travel speeds up to 70 in. per minute. A typical roller is shown in Fig. 3, and applicable processing data are given in the accompanying table.

Before hard facing, the rims and flanges were cleaned with a wire brush to remove rust and earth, and the inside of the tread area was uniformly ground. Working surfaces showing evidence of tears, thinning, or cracks were repaired by shielded metal-arc welding.

No preheating was used. Components that were worn concave were built up with a type 1A alloy, using a uniform stepover, or overlap, pattern for the beads, as shown in Fig. 3, operation 1. When the surfaces were evenly restored, three complete hard facing layers were deposited, using a group 1B alloy and the bead pattern shown in Fig. 3, operation 2. With each complete revolution, a stepover or overlap equivalent to a third to a half of the bead width was employed. The electrode was positioned off-center, in the direction opposite to that of rotation, at a distance of 3/4 to 1 in. for rollers and 1 1/4 to 1 1/2 in. for idlers. The axis of the roller was kept inclined to the horizontal at an angle of 45° to 60°, and that of the idler at 20°. Roller flanges were backed up by a copper plate, which helped to support the flux and to extract heat from the flange.

Current input for the rollers and idlers ranged from 275 to 450 amp and voltage ranged from 28 to 32 volts. Reverse-polarity direct current was used The depth of each layer was between 1/8 and 3/16 in. The number of layers used depended on the amount of wear that had taken place. Travel speed was from 25 to 45 in. per minute for rollers and from 35 to 70 in. per minute for idlers.

To minimize bore shrinkage, the mass of the parts, other than weld surfaces, was kept relatively cool by carefully restricting current (heat) input and by allowing the parts to cool after each layer. In general, the hard facing sequence for a set of rollers consisted of welding one layer on each roller in turn, starting at the outer flange and finishing at the inner flange.



Conditions for Automatic Submerged-Arc Welding

Part	Tractor roller, 5 to 11 in. in width and 7 to 11 in. in outside diameter(a)
Power supply	600-amp transformer-rectifier
Hard facing alloys	Group 1A; group 1B(b)
Current	275 to 450 amp, dcrp
Voltage	28 to 32 v
Travel speed	25 to 45 ipm(c)
Depth of deposited metal	1/8 to 3/16 in.(d)

(a) Tractor idlers (4 to 11 in. wide and 21 to 35 in. in outside diameter) were hard faced in the same way. (b) Group 1A alloy for buildup pass and group 1B alloy for hard facing passes. (c) Travel speed for idlers was 35 to 70 ipm. (d) Each layer had the thickness indicated.

Fig. 3. Tractor roller hard faced using automatic submerged-arc welding, showing details of buildup and hard facing passes (Example 154)

Blades for shearing hot metal are often made of carbon steel (0.50 to 0.80% C) and are used in steel mills to crop, and shear to length, hot slabs, bars and billets. The blade edges are hard faced to retain their sharpness and shape, and to withstand high impact loads without spalling and to resist thermal shock. Blade sizes vary over a wide range, depending on the sizes of stock to be sheared. Examples 164, 165 and 166 describe the hard facing of alloy tool steel shear blades with other tool steels, by various welding processes. The example that follows deals with hard facing a shear blade made of a medium-carbon steel with a group 2A, 2B or 4A alloy by submerged-arc welding.

Example 155. Blades for Hot Shearing (Fig. 4)

A shear blade, 48 by 12 by 8 in. with hard faced cutting edges, is shown in Fig. 4. Before hard facing, the cutting edges of the blade were machined to form suitable stepped recesses, as shown in Fig. 4. Blades were then preheated to 400 to 500 F. Using submerged-arc welding and a 1/8-in.-diam electrode wire, weld metal was deposited on each cutting edge in multiple layers, providing sufficient allowance for final machining or grinding to square corners. Immediately after hard facing, the blades were covered with an asbestos blanket to ensure a slow rate of cooling.

Depending on the service requirements, several types of hard facing alloys were employed, including modified stainless steels, alloys of groups 2A and 2B, and cobalt-base alloys of group 4A. Smaller blades and those requiring cobalt-base alloys (which are not available in wire form) were faced by shielded metal-arc or oxyacetylene welding. Automatic submerged-arc welding was preferred for larger blades because of its high deposition rate and more uniform weld deposit.

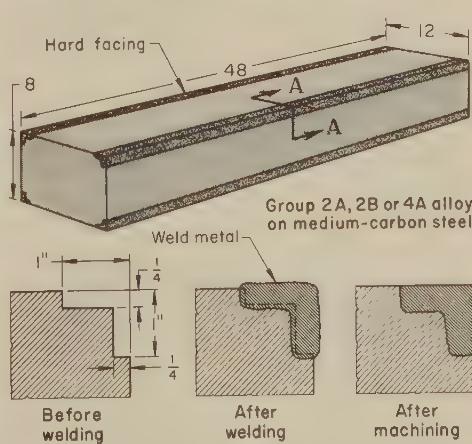


Fig. 4. Typical hot shear blade with hard faced cutting edges, and sectional views of cutting edges before and after welding, and after machining (Example 155)

Surfacing with corrosion-resistant alloys by submerged-arc welding is described in Examples 62, 63 and 64 in the article on Submerged-Arc Welding, which begins on page 46.

Hard Facing by Open-Arc Welding

Open-arc welding is a semiautomatic consumable-electrode process that does not employ either a flux or a shielding gas. It is used to a considerable extent for hard facing (see Examples 148, 151 and 153). The electrode wire, which is fed continuously, is tubular, with alloying elements in the core as powder or granules. These wires contain deoxidizers, but no flux.

A principal advantage of open-arc welding is the low cost of the equipment. Neither flux-handling equipment nor gas-regulating apparatus is required. Thus, it is the simplest semiautomatic welding process, requiring only one accessory — a device to feed the continuous electrode wire. The electrode holder is similar to the electrode holder used for flux-cored arc welding by the self-shielding method.

Open-arc welding produces more weld spatter than the other arc welding processes, but this spatter is rarely objectionable in hard facing applications.

Hard Facing by Gas Metal-Arc Welding

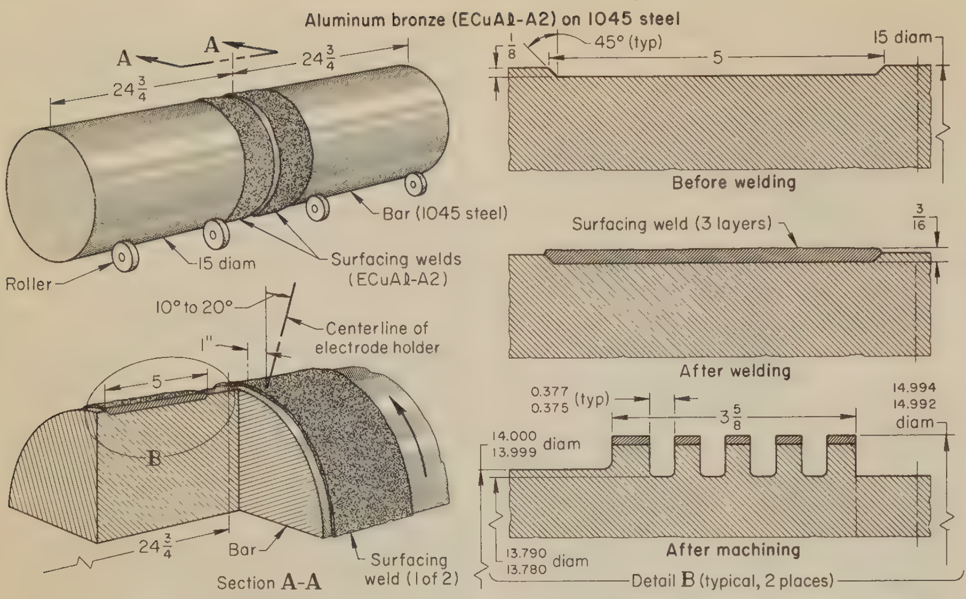
In hard facing by gas metal-arc welding, the arc and weld areas are protected by a flow of shielding gas — carbon dioxide, argon or helium, either singly or in combination, or with a small amount of oxygen. A detailed description of the process is provided in the article on Gas Metal-Arc Welding, which begins on page 78 in this volume.

The use of shielding gases adds to the cost of hard facing, but the higher cost can be justified when the shielding gases prevent weld-metal oxidation and alloy loss and provide required weld quality. Wire electrodes must be used with this process, however, and since some of the hard alloys are not available in wire form, this limits the use of gas metal-arc welding for hard facing.

The application of this process to surfacing steel with bronze and other corrosion-resistant metals is described in Examples 91 to 94 in the article on Gas Metal-Arc Welding, in this volume. The example that follows describes surfacing of a medium-carbon steel piston with a wear-resistant aluminum bronze (see also Example 159).

Example 156. Choice of Gas Metal-Arc Welding Over Alternative Processes for Quality and Speed in Surfacing a Piston With Aluminum Bronze (Fig. 5)

Lands between the piston-ring grooves in heavy-duty hydraulic pistons were surfaced with aluminum bronze to make a bearing surface for sliding contact with the



Conditions for Surfacing by Gas Metal-Arc Welding

Power supply	500-amp rectifier(a)	Number of layers	Three
Electrode wire	1/16-in.-diam ECuAl-A2	Weight of filler metal deposited per piece(b)	20 lb
Current	260 to 280 amp, dcrp	Deposition rate	0.0833 lb per min(c)
Voltage	24 to 27 v	Welding time per piece(b)	4 hr(c)
Shielding gas	Argon, at 45 cfh	Preheat	400 to 450 F for 3 hr
Work-rotation speed	14 to 16 surface in. per min	Postheat	400 to 450 F; cover, cool slowly

(a) Three-phase, constant-voltage type. (b) Two pistons. (c) In surfacing by shielded metal-arc welding, time per piece (two pistons) had been 12 hr (deposition, 0.027 lb per min); by gas tungsten-arc welding, 14 hr (0.0238 lb per min).

Fig. 5. Surfacing of two heavy-duty pistons head-to-head in a single length of bar, to obtain wear-resistant lands after machining. For this application, gas metal-arc welding was considerably faster than two processes previously used. (Example 156)

cylinder walls. As shown in Fig. 5, the pistons were made in pairs from a 15-in.-diam solid bar of 1045 steel, and were positioned head-to-head in the bar with an allowance of 2 in. between them for machining. Before the pistons were cut apart, a 5-in. span at the head of each cylinder was undercut ⅛ in. to accommodate the surfacing weld; then the pair of pistons was surfaced as a single unit before being cut apart and finish machined (see detail B in Fig. 5).

At first, shielded metal-arc welding with covered aluminum bronze electrodes was tried, but it produced an extremely porous surface weld containing many inclusions and voids, which necessitated a great deal of repair welding. The time required for making the surfacing welds on one pair of pistons was 12 hr.

When the method was changed to semiautomatic gas tungsten-arc welding, surface condition was good, and repair welding was considerably reduced. However, more welding time was needed (14 hr per pair of pistons) than with the shielded metal-arc process, and cost was excessive.

To reduce cost and production time, automatic gas metal-arc welding was tried. With this method, surfacing time was reduced to 4 hr per pair of pistons, and the quality of the deposit was acceptable.

For gas metal-arc surfacing, the piston blank was placed on rollers that turned it at a surface speed of 14 to 16 in. per minute. Equipment was provided to cause the electrode (positioned as shown in section A-A in Fig. 5) to step over approximately 5/32 to 3/16 in. with every revolution of the blank. This stepover produced an overlap slightly more than 50% of the width of the weld bead.

Details of the procedure using gas metal-arc welding are summarized in the table appearing with Fig. 5.

Hard Facing by Gas Tungsten-Arc Welding

Gas tungsten-arc welding (described in detail in the article that begins on page 113) offers several advantages in hard facing. Either the torch can be used manually or the process can be automated by attaching the torch to an oscillating mechanism and using a device to feed the hard facing filler metal into the arc region. By controlling the wire feed, width of oscillation, and travel speed, a closely controlled deposit can be obtained. The arc action is smooth, quiet and free of weld spatter, and produces high-quality hard facing deposits. The weld puddle can be controlled to permit out-of-position overlay applications. Hard facing alloys can be used in either rod or wire form.

There are some disadvantages to gas tungsten-arc welding for hard facing. A dilution of at least 10% is almost unavoidable. The argon or helium gas shield, which is relatively expensive, must be protected from air drafts to ensure its effectiveness. Deposition is so slow that the use of gas tungsten-arc welding for hard facing is limited to minor repairs and small parts.

The following example compares manual and automatic methods for hard facing by gas tungsten-arc welding.

Example 157. Manual vs Automatic Gas Tungsten-Arc Welding for Hard Facing of Valve Gates (Fig. 6)

Valve gates made of 4140 steel forgings, with typical dimensions and characteristic patterns of hard facing deposits developed by manual and automatic gas tungsten-arc welding, are shown in Fig 6. Both methods employed a 500-amp rectifier as power supply and a 3/16-in.-diam group 4A cobalt-base alloy rod (1.09% C, 26.25% Cr, 7.01% Fe, 4.22% W) for the overlay. A 300-amp torch was used with the manual method, and a 500-amp torch with the automatic method. Preparation of the workpiece (cleaning and machining the surfaces to be hard faced) was identical for both methods; no preheat was used in either method. The major differences between the methods were in the tooling and the weld patterns of the deposits. The manual method, without special tooling, deposited a coating to cover the entire front surface of the plate (see Fig. 6, Manual method). By using a variable-speed rotating table, an oscillating mechanism for the torch, and a cold-wire feeding mechanism for the alloy rod, the automatic method provided selective deposition on the surfaces, as shown in Fig. 6, Automatic welding. Thickness of deposit was about ⅛ in. After hard facing, the valve gates were stress relieved at 1150 F.

The following comparative data for the two methods were obtained:

Item	Manual	Automatic
Hard facing time:		
Pressure end, min	33.4	5.72
Fluid end, min	29.4	5.72
Total arc time, min	62.8	11.44
Deposition rate, lb per hour	1.84	2.75
Area hard faced, sq in.	23.4	18.4
Hard facing alloy consumed, lb	1.93	0.525

The automatic technique was faster and more economical, requiring less hard facing alloy than the manual method. It also resulted in fewer weld defects.

Prevention of Surface Cracks. Some of the most effective abrasion-resistant alloy coatings are susceptible to cracking, which can be aggravated by thermal gradients developed during welding and by marked differences in the thermal expansion-contraction characteristics of the base metal and the overlay. The most common measure employed to avert surface cracking is preheating the work. Another effective method is the application of a less crack-susceptible buttering layer, as described in the following example.

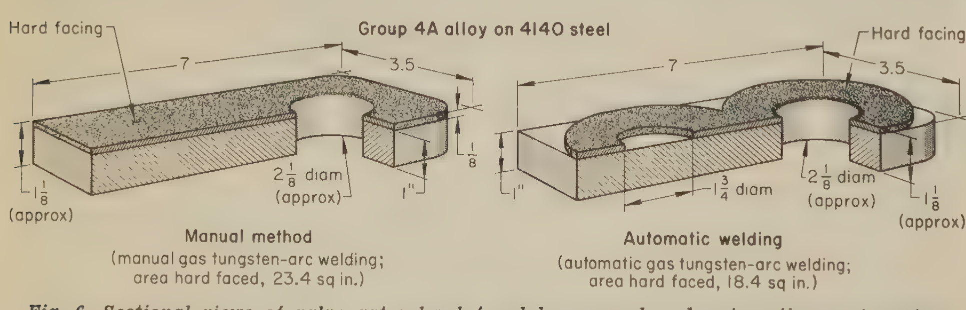


Fig. 6. Sectional views of valve gates hard faced by manual and automatic gas tungsten-arc welding. Because of selective deposition when using the automatic method, a smaller quantity of hard facing alloy was consumed. (Example 157)

Example 158. Use of a Buttering Pass To Prevent Cracking of a Brittle Overlay on Tool Fixtures (Fig. 7)

Tool fixtures used to finish bore connecting-rod assemblies were produced from blanks 5⅝ in. in outside diameter and 1 in. thick, of 3120 steel. After preliminary machining of the blank, a cobalt-base hard facing alloy of group 4A (nominal composition: 2.5% C, 30% Cr, 12% W) was deposited to obtain two raised-face areas, as shown in Fig. 7. The surfacing was done by manual gas tungsten-arc welding, using argon gas to shield the weld area; good deposition control was needed to ensure that the overlay was limited to the specified areas. After hard facing, the tool fixture was heat treated to Rockwell C 45 to 50; the two raised areas were subsequently surface ground to size.

Selection of the group 4A hard facing alloy was based on hardness (Rockwell C 54) and resistance to metal-to-metal wear (especially to galling), but because of brittleness of the deposited layer, about 85% of the welds cracked, resulting in frequent rejections and the need for weld repairs. Investigation revealed that cracking could be overcome by depositing an initial layer of a softer and tougher group 4A cobalt-base alloy (1.10% C, 28% Cr, 4% W). This alloy had a hardness of Rockwell C 44, a tensile strength of 105,000 psi, and good resistance to impact and thermal shock. As a result of this modification, rejections for cracking of the final hard facing deposit were reduced to 1% of the total number of welds made.

The procedure for making the initial pass consisted first in machining a 1⁄16-in.-deep recess at the inner circular edge of the tool fixture (Fig. 7, Before welding). This recess was then filled with the more ductile group 4A filler metal. The final pass was made with the harder group 4A filler metal, covering the areas shown in Fig. 7, After welding. The completed two-layer deposit was machined and ground to the dimensions shown in Fig. 7, After machining. The welding conditions for both passes are given in the table accompanying Fig. 7.

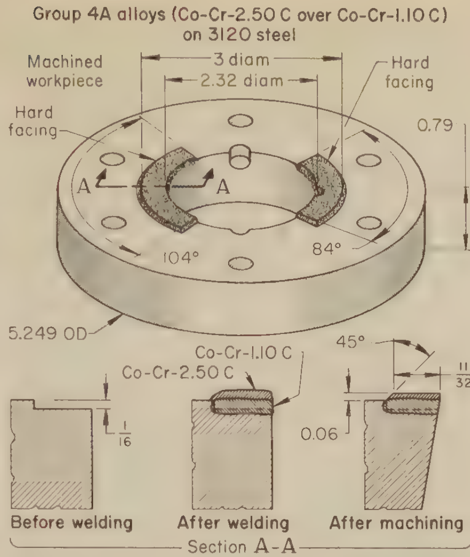
Effect of Overlay Composition on Wear Resistance. Because of the large variation in service conditions, predicting the performance of a given alloy is difficult, especially if experience under similar conditions is not available. A seemingly small change in the alloy used for hard facing, or the method, or both, may have a large effect on results. One such application is described in the example that follows.

Example 159. Change of Surfacing Alloy and Method of Welding To Prolong the Life of Pot Plungers (Fig. 8)

Pot plungers (pistons) like the one shown in Fig. 8 were used in hydraulic presses, for injection molding of rubber compounds in and around metal parts. The low-carbon steel plungers operated in heat treated 4140 steel pots with a clearance of 0.001 in.

Originally, the bearing surfaces of the plungers were overlaid with a low-fuming brass (such as RCuZn-E) to prevent galling and seizing of the plunger in the pot. Oxyacetylene welding was used for surfacing with this alloy. Because of the abrasiveness of the rubber compounds, the maximum service life of the plungers was 30 days, which was not acceptable.

Service life was extended to 24 to 36 months by changing the facing alloy to a hard, wear-resistant aluminum bronze (RCuAl-D), deposited by gas tungsten-arc welding. Oxyacetylene welding was not suitable for use with aluminum bronze, because the aluminum oxides that formed in the oxyacetylene flame rendered the use of conventional fluxes difficult and interfered with smooth metal deposition. Gas tungsten-arc welding required no flux and the argon shielding provided adequate protection against contamination.

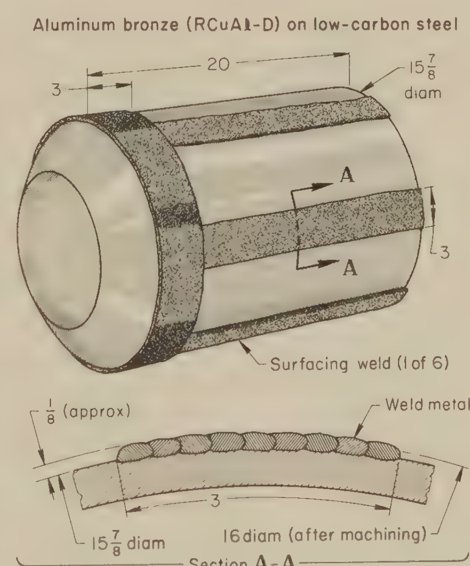


Conditions for Manual Gas Tungsten-Arc Welding

Power supply	300-amp transformer-rectifier, with high-frequency, foot-operated control
Electrode	1⁄16-in.-diam EWTh-2
Hard facing alloy	⅛-in.-diam group 4A(a)
Torch	200 amp, water cooled; with gas lens
Shielding gas	Argon, at 24 to 26 cfh
Welding position	Flat
Welding fixtures	None
Current	110 to 120 amp, dcsp
Arc starting	High frequency

(a) Alloy with 1.10% C for buttering pass; alloy with 2.5% C for surface pass.

Fig. 7. Tool fixture for finish boring of connecting rods, showing two areas built up by hard facing, using gas tungsten-arc welding (Example 158)



Conditions for Hard Facing by Gas Tungsten-Arc Welding

Welding position	Flat
Power supply	500-amp transformer-rectifier
Current	250 to 400 amp, dcsp
Voltage	Not regulated
Torch	500 amp, water cooled; ½-in.-diam cup
Electrode	5⁄32-in.-diam EWTh-2, taper ground
Filler metal	3⁄16-in.-diam RCuAl-D
Shielding gas	Argon, at 15 to 20 cfh
Welding speed	8 ipm

Fig. 8. Pot plunger surfaced in specific areas with aluminum bronze by gas tungsten-arc welding (Example 159)

Before surfacing, the outside of the steel plunger was sand blasted and cleaned with a wire brush. Preheating was not required. Weld beads, about ⅜ in. wide and ⅛ in. deep, were deposited longitudinally in a parallel, overlapping sequence, around the bearing-surface area, to form a band 3 in. wide. A second series of beads of the same size was deposited (in the same direction) to form six uniformly spaced bands, 3 in. wide, running lengthwise along the surface of the plunger. Welding was done in the flat position, and because of the rapid dissipation of heat by the mass of the plunger body, the surfacing operation was continuous. The aluminum bronze rods were 3⁄16 in. in diameter and 36 in. long. Electrodes were pointed, thoriated tungsten rods, and were 5⁄32 in. in diameter.

After surfacing was completed, the overlay was machined to a thickness of 1⁄16 in. A machining tolerance of 0.0005 in. was provided on the finished diameter, because specifications required the clearance between the plunger and pot to be 0.001 in. After machining, two longitudinal grooves ⅛ in. wide and 1⁄16 in. deep were cut in the overlay at the bearing surface to relieve air pressure and backflow of the rubber compound during plunging. Additional welding details are presented in the table that is included with Fig. 8.

Hard Facing by Plasma-Arc Welding

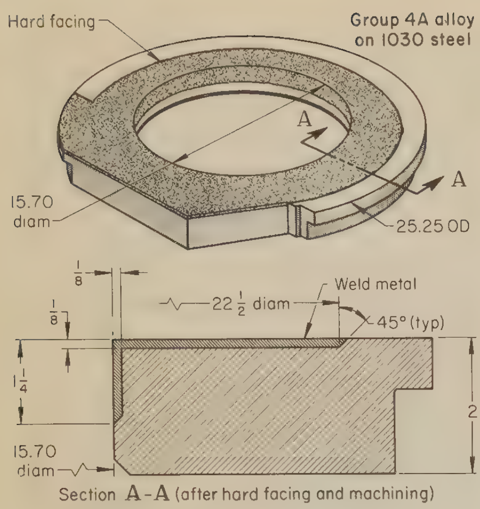
In hard facing by plasma-arc welding, the filler metal, in powder form, along with the plasma jet, is forced through a constricting orifice and accelerated to sonic velocity with intense heat (30,000 F) to form a bond with the base metal. A conventional direct-current power supply, connected in straight polarity, is used to maintain the arc and control the amount of heat input to the work. Plasma-arc welding as a joining process is discussed in detail in the article that begins on page 138 in this volume.

Plasma-arc welding enables high-density coatings of virtually any material or compound to be applied, provided that the material can be supplied in the appropriate particle-size range (−200 to +325 mesh), preferably in spheroidal form, and that it will conduct electricity, and will not undergo sublimation.

Among the advantages of plasma-arc hard facing is the ability of the process to limit penetration into the base metal to as little as 0.005 in., and to control base-metal dilution between 5 and 30%. Single-pass deposits between 0.010 and ¼ in. in thickness and ⅛ to 1¼ in. in width can be closely controlled. Greater widths can be developed. Speeds of more than 20 in. per minute are obtainable with 95% deposition efficiency. A wide selection of alloy powders is available for hard facing, and deposits are generally flatter and smoother than those produced by other arc welding processes, features that can reduce material and finishing costs.

Disadvantages of plasma-arc welding for hard facing are the high cost of equipment, the skill and knowledge required of the welding operator, and the need to bring the workpiece to the machine.

The successful use of plasma-arc welding in hard facing a component used in a rubber-compounding machine is described in the following example.



Conditions for Hard Facing by Plasma-Arc Welding

Power supply	600-amp rectifier
Hard facing alloy	Group 4A(a)
Argon flow	To arc, 8 cfh; with powder, 10 cfh; for shielding, 45 cfh
Preheat and postheat	None
Surface finish	Ground
Travel speed	3 ipm
Depth of deposited metal	3/16 in. (two 3/32-in. layers)
Width of deposited metal	3/4 in.

(a) Cobalt-base alloy with 2.5% C, 30% Cr, 12% W. Other high-carbon group 4A alloys were also satisfactory.

Fig. 9. Banbury-mixer rotor end plate that was hard faced more economically by plasma-arc welding than by shielded metal-arc welding (Example 160)

Example 160. Plasma-Arc Facing of Rotor End Plates for Banbury Mixers (Fig. 9)

Rotor end plates of Banbury mixers, used for compounding rubber, are subjected to severe abrasive wear during service. To improve their resistance to abrasion, rotor end plates (Fig. 9) made of 1030 steel were traditionally either chromium plated, carburized, or hard faced. For hard facing, shielded metal-arc welding was used until it was established that plasma-arc welding was more economical and about three times as fast.

The circular parts to be hard faced were set on a welding positioner equipped with a speed reducer capable of producing speeds down to one revolution in 30 min. The parts were positioned so that the welding head could progress linearly across the surface to be coated. The plasma-arc welding machine was equipped with power feed and a head-traversing mechanism; power was supplied from a 600-amp rectifier. With the torch 5/8 in. from the workpiece, a weaving pass was employed to produce a deposit 3/4 in. wide. The welding head had a period of oscillation of 3 sec, and an amplitude of 1 in. Linear deposition rate was 3 in. per minute. Argon gas was used to maintain the arc, feed the alloy powder, as well as to shield the arc.

A group 4A cobalt-base alloy powder (2.5% C, 30% Cr, 12% W) was fed at a rate of 33 grams per minute. Two layers, each with a deposit thickness of 3/32 in., were made. No preheating or postheating was required. After completion of the second layer, the deposits were ground to finished size. Additional details for hard facing by plasma-arc welding are given in the table accompanying Fig. 9.

Compared with shielded metal-arc welding, plasma-arc welding resulted in a large reduction in processing time and a saving in metal because there were no unused electrode ends. The use of a process that did not involve the need for a flux was also advantageous.

In the following example, plasma-arc hard facing competed successfully with hard facing by gas welding.

Example 161. Oxyacetylene vs Plasma-Arc Welding for Hard Facing of Valve Seats (Fig. 10)

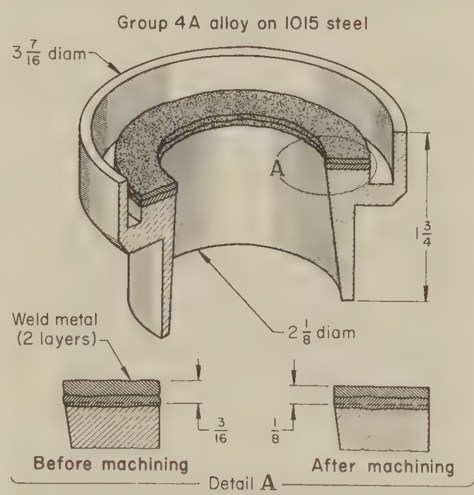
For purposes of comparison, oxyacetylene and plasma-arc welding were used for the hard facing of valve seats made of 1015 steel tubing and used in high-pressure steam-flow boiler-cleaning equipment. A sectional view of a typical valve seat, with dimensions, is shown in Fig. 10.

For oxyacetylene welding, the workpiece was first preheated to between 800 and 1350 F, and then a group 4A cobalt-base alloy (1.10% C, 28.0% Cr, 4.0% W) was deposited, using a 1/8-in. filler rod. Three layers were required to develop a deposit 1/4 in. thick. Total welding time per piece was 20 min. The operation was entirely manual and required the minimum of equipment. Other processing details are given in the table accompanying Fig. 10.

Plasma-arc hard facing, which was installed to replace the oxyacetylene process, was completely automatic and required only two layers. Elapsed time was 2 min, 24 sec to deposit a coating 3/16 in. thick. Major equipment was: a sequence programer, a 75-amp ac oscillator for the nontransferred arc, a 500-amp rectifier for the transferred arc, slope and timing controls, automatic power feed, guidance fixtures and positioners, gas shielding fixtures, and a plasma-arc torch.

The sequence of operations began with the cleaning of the part to remove rust, grease, and other soils that might cause porosity. The part was then placed in a holding and rotating fixture, and the plasma torch was set in position. No preheating was required. The entire hard facing sequence was controlled by the sequence programer. Welding was done in the flat position, using an arc length of 3/8 in. and a transferred-arc power setting of 79 amp. A cobalt-base alloy of group 4A (1.60% C, 28% Cr, 3% Ni, 4% W) in powder form was used for hard facing. Two layers, each 3/32 in. thick, were deposited (see Fig. 10); the interpass temperature was 500 F. Postheating was not required. After removal from the fixture, the hard faced surfaces were ground to finished dimensions, as shown in Fig. 10. Surface finish was 32 micro-in. Dye-penetrant inspection was employed to detect cracks and other surface defects.

The plasma-arc welding method reduced welding time by 87%, material cost by 10%, and weld repair work by 95%, compared with oxyacetylene welding.



Item	Oxyacetylene welding(a)	Plasma-arc welding(b)
Hard facing alloy	4A(c)	4A(d)
Preheat	800 to 1350 F	None
Postheat	None(e)	None
Number of layers	Three	Two
Weld time	20 min	2 min, 24 sec
Surface finish	Ground	Ground
Depth of deposit	1/4 in.	3/16 in.

(a) Fuel-gas flow: acetylene, 4 to 6 psi; oxygen, 7 to 9 psi. (b) Power supply: for nontransferred arc, 75-amp ac oscillator; for transferred arc, 500-amp dc rectifier. Argon flow: to arc, 9 to 11 cfh; with powder, 14 to 15 cfh; for shielding, 43 to 47 cfh. (c) Cobalt-base alloy with 1.10% C, 28% Cr, 4% W. (d) Cobalt-base alloy with 1.60% C, 28% Cr, 3% Ni, 4% W. (e) The hard faced stainless steel valve seats were cooled slowly in asbestos.

Fig. 10. Valve seat with hard facing layer deposited by plasma-arc welding (Example 161)

Comparison of Welding Processes

In rotary oil-well drilling, there is considerable abrasive wear on the shoulder areas of the joint used to connect sections of drill pipe, as the pipe rotates and moves up and down in the hole. The replacement costs for the tool joint justify the expense of hard facing, particularly when abrasive rock formations are being drilled. In directional drilling, especially in offshore operations, drilling is done through a casing. When a hard facing layer consists of fine particles of tungsten carbide embedded in a matrix of low-carbon steel, the deposits on the joints are less abrasive to the casing and yet retain high wear resistance.

A comparison was made of four welding processes used in hard facing of drill joints with this carbide-steel composite: manual oxyacetylene, automatic gas metal-arc, gas tungsten-arc, and plasma-arc welding. The working details of each process, and the relevant advantages of the three arc welding processes over oxyacetylene welding for this application, are discussed in the example that follows.

Example 162. Comparison of Four Welding Processes for Hard Facing of Tool Joints (Fig. 11; Table 4)

The design of a typical tool joint for rotary oil-well drilling is shown in Fig. 11. Joints varied in size as follows (see Fig. 11 for location of dimensions).

Size, in.	2 7/8	3 1/2	4 1/2	5
Weight, lb	34	41	74	122
Length, in.	14	16	17	17
Dimension D_1, in.	3	3 5/8	4 5/8	5 1/4
Dimension d, in.	1 7/8	2 7/16	3 1/4	3 3/4
Dimension D_2, in.	4 1/2	4 3/4	6	6 1/4

Tool joints were made of 4137H steel, oil quenched and tempered to 311 to 341 Bhn. The deposition of a wear-resistant coating of tungsten carbide particles in a matrix of low-carbon steel onto the tool joint by each of the four welding processes is discussed below.

Oxyacetylene Welding. The tool joint was first positioned on a turning mechanism actuated by a foot pedal, with the axis of the joint horizontal, the threaded end toward the welder. The part was cleaned and preheated to 400 to 600 F, using an indicating crayon to check the temperature.

By shielded metal-arc welding, stringer beads intended to serve as guide ribs for hard facing were deposited circumferentially along the area to be hard faced. The ribs were about 1/16 in. high and were spaced about 7/8 in. apart. They were interrupted every 120° by a gap of about 1/2 in.; the interruptions in successive ribs were staggered. Where previous hard facing was still visible, new ribs were deposited directly on the old ones.

After depositing the guide ribs, flux and weld spatter were removed from the surface. Hard facing alloy was deposited man-

ually, starting in the groove nearest the threaded end. Deposition continued in the direction of the tapered elevator shoulder, ending in a blend at the shoulder. The backhand technique was used, and a slight excess of acetylene. The depth of tungsten carbide deposited was approximately 1⁄16 in. Every effort was made to obtain a good bond with minimum puddling. The base-metal temperature, measured at a distance of 4 in. from the tool-joint shoulder, was not permitted to exceed 700 F. After hard facing, the joint was cooled in still air.

Gas Metal-Arc Welding. The tool joint was grooved as shown in detail A of Fig. 11, and preheated to 600 to 800 F. It was positioned so that the 18° tapered shoulder was horizontal, and the positions of the electrode holder and carbide feed were approximately as shown in Fig. 11, angle *a* and distances *m* and *w* being determined by trial and error. First, hard facing was applied to the tapered elevator shoulder, tungsten carbide being fed into the molten hard facing puddle immediately behind the arc. The part was then repositioned so that its centerline was horizontal. The filler metal and tungsten carbide were deposited, smoothly overlapping the initial deposit at the shoulder. The welding head was then indexed automatically so that each successive bead overlapped the preceding bead by about 1⁄8 in. After hard facing, the tool joint was cooled in air.

Gas Tungsten-Arc Welding. The procedure for gas tungsten-arc hard facing, including the location of the torch and carbide feed nozzle, was similar to that used for gas metal-arc welding except that the outside of the tool joint was not grooved for hard facing and the tungsten carbide was introduced differently. The surface of the base metal was brought to fusion temperature by the heat of the arc, and the tungsten carbide particles were fed onto the molten surface. As the weld metal solidified, a coating of carbide particles dispersed in a matrix of the base metal was obtained.

Plasma-Arc Welding. The plasma-arc process was an automatic operation similar to the gas metal-arc process, except that a plasma-arc torch was employed and iron powder was substituted for the 1⁄16-in.-diam consumable electrode wire.

Comparison. Details of welding conditions and cost data for the four processes are given in Table 4. A comparison of the three arc welding methods with oxyacetylene welding led to the following conclusions:

1 The arc welding processes could be readily automated, and hence were three to five times faster than oxyacetylene welding.
2 Equipment cost for automatic arc welding was much higher than for oxyacetylene welding. Initial investment in equipment for plasma-arc welding was about twice that for gas tungsten-arc or gas metal-arc welding and ten times that for oxyacetylene welding.
3 Labor cost (indicated by hard facing time in Table 4) was much higher for manual oxyacetylene welding than for automatic arc welding

Hard Facing of Austenitic Manganese Steel

Austenitic manganese steel (Hadfield's steel) is a tough, wear-resistant, nonmagnetic alloy usually containing 1.0 to 1.4% C and 10 to 14% Mn; it is available in cast and wrought forms. The high manganese content has an austenite-stabilizing effect; the usual hardening transformation is suppressed, and the austenite is completely retained when the steel is cooled rapidly from a high temperature to room temperature. The as-quenched steel is in a metastable condition, and, on moderate reheating, instead of the usual softening and increase in ductility, manganese steel becomes embrittled by partial transformation of the metastable austenite. Consequently, the welding and hard facing of manganese steel require techniques that will result in a minimum heat buildup.

Before hard facing, the surface of the manganese steel base metal should be clean, sound, and in the non-work-hardened condition. Grinding or air carbon-arc cutting can be used to remove work-hardened metal. Cracks and

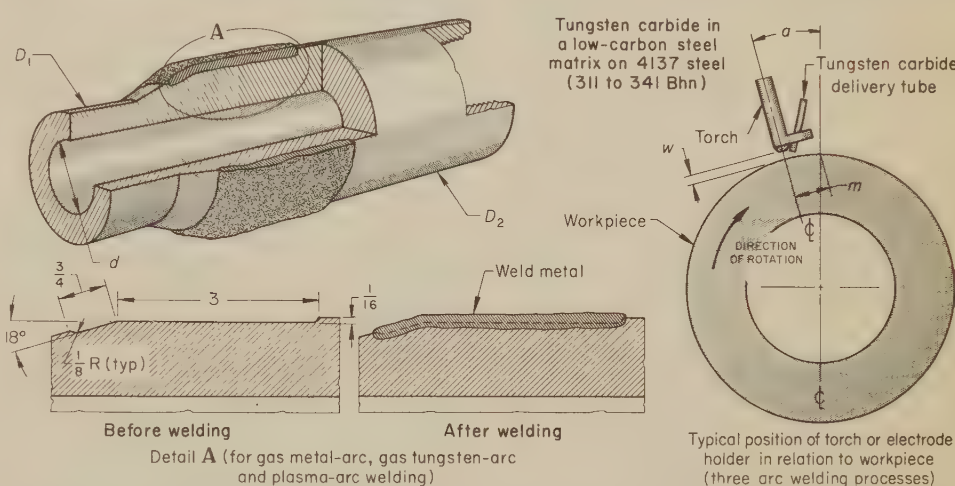


Fig. 11. Tool joint for oil-well drilling, showing the area that was hard faced, and sections through the weld groove before and after welding. Positions of torch or electrode holder and carbide feed tube are shown at the right. Values of a, m and w were determined by trial and error. See Table 4 for a comparison of data for four welding processes. (Example 162)

Table 4. Operating Conditions and Cost Factors for Hard Facing Joints on 4137H Steel Tools (See Fig. 11) by Four Welding Processes (Example 162)

Item	Oxyacetylene welding(a)	Gas metal-arc welding	Gas tungsten-arc welding	Plasma-arc welding
Mode	Manual	Automatic; oscillating	Automatic	Automatic; oscillating
Hard facing alloy	3⁄16 to 1⁄4-in.-diam steel tube binder; 20-mesh tungsten carbide filler(b)	1⁄16-in.-diam low-carbon steel wire; 20 or 50-mesh tungsten carbide granules	20 or 50-mesh tungsten carbide granules	Iron-base powder; 20 or 50-mesh tungsten carbide granules
Layer depth, in.	1⁄16 to 3⁄32	1⁄16 to 3⁄32	1⁄16 to 3⁄32	1⁄16 to 3⁄32
Power supply	....	500-amp direct current	300-amp direct current	500-amp, transferred arc; 75-amp, nontransferred arc
Hard facing alloy feed	Manual	Variable carbide feed	Variable carbide feed	Variable carbide feed
Fuel-gas flow	Acetylene, at 49 to 62 cfh; oxygen, at 53 to 65 cfh	....	....	....
Shielding	Flux	Argon, at 30 to 35 cfh	Helium, at 70 cfh	Argon, at 70 cfh(c)
Current, amp	....	340 to 360, dcrp	240 to 260, dcsp	300 to 360, dc, transferred arc; 65, dc, nontransferred arc
Voltage, v	....	29 to 32	40	29 to 32
Number of passes	....	5	15	5
Bead width, in.	....	7⁄8	1⁄4	7⁄8
Surface speed	2.25 to 2.50 sq in./min	18 to 20 ipm	36 ipm	18 to 20 ipm
Tungsten carbide flow	....	600 grams/min	250 grams/min	600 grams/min(d)
Oscillations per minute	....	80 to 110, 3⁄4 in. wide	....	70 to 90, 3⁄4 in. wide
Arc time, minutes	....	4½	7½	4½
Preheat, F	400 to 600(e)	600 to 800(f)	600 to 800(f)	600 to 800(f)
Costs for Hard Facing 100 6-In.-OD Tool Joints				
Shielding gas	....	$ 24.00	$105.00	$ 48.00
Oxygen	$ 6.20	....	....	....
Acetylene	25.10	....	....	....
Tungsten carbide	485.00	615.00	550.00	615.00
Wire or powder	....	22.00	....	198.00
Total	$516.30	$661.00	$655.00	$861.00
Hard facing time, min	2500	450	750	450
Equipment cost	$1,000	$5000	$5,000	$10,000

(a) Shielded metal-arc welding was used to deposit strings of beads that served as guide ribs for hard facing. Power for shielded metal-arc welding was supplied by a 200-amp unit; electrodes were 3⁄32 to 1⁄8-in.-diam E6010 or E6012. (b) 40% binder; remainder filler. (c) Includes argon for powder, shielding gas and orifice flow. (d) Iron powder flow, 100 grams/min. (e) Gas burner, furnace, or induction coil. (f) Induction coil.

other defects should be repaired by welding, using electrodes of austenitic manganese steel or related austenitic alloys. Except in extremely cold weather, manganese steel should not be preheated, and never above 200 F. The welding current and time must be adjusted to avoid overheating. Heat buildup can be minimized by skip welding — welding alternately on several parts — or by using an auxiliary cooling arrangement for the part.

Only arc welding is recommended for hard facing manganese steel components. Oxyacetylene welding is likely to be harmful, because of the relatively long period of heating involved. Arc length should be kept short and current input relatively low, so as to ensure arc stability and complete fusion bonding, while minimizing heat accumulation in the part.

Most covered electrodes for welding austenitic manganese steel can be used with the common power supplies (motor-generators, rectifiers and transformers). Most continuous wire electrodes for semiautomatic or automatic welding are used with direct current only. Small-diameter manual welding electrodes commonly have deposition rates of less than 2 lb per hour. At higher welding currents, and with the use of large-diameter heavily coated electrodes, deposition rates of 8 to 10 lb per hour can be obtained. Continuous-wire electrodes can deposit at rates as high as 15 lb per hour, and even higher.

When hard facing with high-chromium irons and other brittle wear-resistant alloys, checking of weld beads is normal and usually beneficial. These checks (small cracks across the bead) are superficial and do not penetrate into the tougher manganese steel base metal. On large parts, a regular check pattern helps to prevent stress buildup, which otherwise might cause failure of the part during service. Brittle facing materials are not applied in thicknesses of more than two or three layers.

To illustrate the hard facing of austenitic manganese steel, several applications involving mining-equipment components are described in the following paragraphs.

Dragline buckets are subjected to severe abrasive wear over most of their surface area during service. In handling hot slag, wear is accelerated by the abrasive action of the slag at elevated temperatures. To combat wear, buckets are commonly hard faced with semi-austenitic and austenitic high-chromium irons, notably the higher-carbon irons of groups 2A, 2B and 3A. Before hard facing, austenitic manganese steels of group 2C, or variations of these steels, are used to build up worn surfaces. In some areas of the buckets, the less-expensive group 1A alloys can be used for buildup.

A typical dragline bucket, after hard facing, is shown in Fig. 12. Note that the areas subjected to the most severe wear are protected by wear plates, which are welded to the bucket and then hard faced. These "heel" areas and the inside surfaces of the bucket are normally coated with a higher-alloy material, to provide maximum wear resistance. Other surfaces are

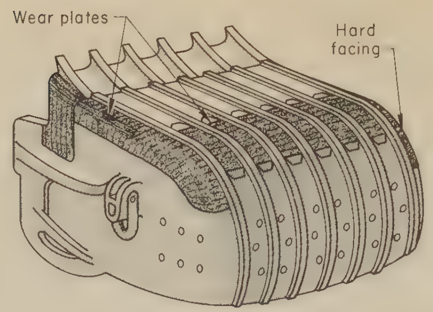


Fig. 12. Dragline bucket, showing hard facing on teeth, lips, wear plates, and other areas subject to wear

faced with a semiaustenitic material, which provides good abrasion resistance at moderate cost. Dragline buckets are frequently hard faced in the field, using shielded metal-arc welding or open-arc welding.

Before hard facing, badly worn bucket lips are built up with manganese steel to provide strength and support for the overlay. The lips and teeth are then hard faced only on the top with a solid layer of semiaustenitic alloy or a high-chromium alloy, depending on the severity of the wear encountered. Teeth and lips are self-sharpening when they are hard faced on the top only. When both top and bottom are hard faced, the teeth and lips become blunt. Most other external and internal surfaces are protected by stringer beads, spaced about ½ in. apart or arranged in suitable patterns.

Common stringer-bead patterns include line, crosshatch, herringbone, and waffle designs. The pattern most effective for a given application is determined by trial. During operation of the dragline bucket, pockets of abrasive material that collect between the facing beads add to the wear resistance of the part. Accordingly, where the operation entails working with loose abrasive material, parallel stringer beads are usually, but not always, laid perpendicular to the flow of material. For example, when rock is being worked, common practice is to use line stringers of hard facing placed parallel to the flow of the rock. Line stringers act as rails and assist the rock flow. Beads that are perpendicular to rock flow cause bumping. For sand, however, perpendicular beads are better. When both sand and rock are being worked, a diagonal crosshatch bead pattern is used. A judicious choice of stringer-bead pattern will help to conserve hard facing material and to minimize welding time; it will also minimize heat

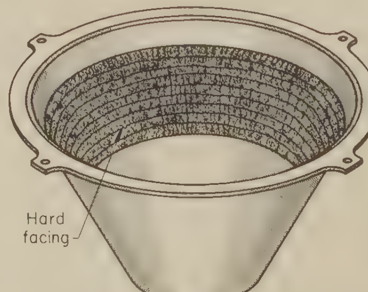


Fig. 13. Gyratory crusher liner with hard facing in the interior

input and help to hold down the overall weight of the part.

By the use of wear strips and hard facing, the service life of manganese steel dragline buckets can be increased considerably beyond that of bare (unfaced) buckets.

Crusher Liners. The hard facing of a manganese steel gyratory crusher liner, such as that shown in Fig. 13, is done with high-alloy materials having compositions similar to high-carbon alloys in groups 2A and 3A. Steels similar to the lower-carbon grades in groups 2A and 2B are also used, although they are less resistant to wear. In general, for a given application, the most abrasion-resistant material capable of withstanding the impact involved is selected for the overlay. Austenitic manganese steel electrodes of group 2C, or related austenitic alloys, are used for buildup.

Either shielded metal-arc welding or open-arc welding with continuous wire is suitable for buildup and for hard facing. Submerged-arc welding has been used, but it is likely to heat the base metal excessively. If equipment is available, automatic welding with a continuous-wire electrode is preferred. When manual welding is employed, the liner can be placed on a turning jig or on its side on the floor so that welding can be done in the flat position.

Before a worn crusher liner is welded, the surface is cleaned and inspected for structural defects. Minor defects are repaired by shielded metal-arc welding. If major defects are encountered and the liner is badly worn, it should be discarded. If buildup before facing is done manually, the use of round bars of manganese steel as inserts may greatly expedite the operation.

In a typical hard facing application employing automatic open-arc welding, the liner is mounted on a rotating positioner, the holding fixture permitting expansion and contraction of the part during welding. The welding head is mounted on a jib that is capable of reaching the inside surfaces. Hard facing begins at the smaller end of the liner, using a semiaustenitic or austenitic high-chromium alloy. The welding head is positioned at the bottom center of the part, with a slight lead, to provide the desired bead contour. Beads are about ⅛ in. high, and are overlapped to provide a surface having slight ridges.

The rotational speed of the positioner is varied to adjust for diameter changes of the liner, so as to keep the surface speed at the weld area constant as welding progresses in a spiral fashion, from the smaller to the larger end. An alternative practice is to space the first few full-turn beads a few inches apart, and then go back and fill in the intervening spaces. Welding is stopped for a short time if the base-metal temperature approaches 500 F, to allow the part to cool slightly and to keep the expansion relatively uniform. Prolonged heating above approximately 200 F is detrimental, not only to metal structure but also in its effect on work-metal shrinkage, distortion, stress buildup, and deposit check pattern. A check pattern, if not self-induced, is obtained by wiping the hot deposit with a wet

cloth or by lightly spraying it with water. Water cooling also keeps heat buildup low enough that welding can continue almost without interruption.

Hard facing alloys, particularly the more wear-resistant grades, are normally applied in two layers, or, at the most, in three layers. About 75 to 100 lb of electrode wire is required to hard face a liner 3 ft in diameter. Successful application and the development of an appropriate overlay pattern require careful study of the particular crusher. Placing an extra layer of hard facing, or using a more wear-resistant alloy at the sizing area or a tougher alloy for the upper section, are typical decisions that result from a study of the particular application.

Power-Shovel Bucket Teeth. Semiaustenitic or austenitic high-chromium irons, similar to some of the higher-carbon group 2 and 3 alloys, are excellent for most conditions of severe wear on bucket teeth. Where impact is severe and abrasion moderate, the martensitic steels of group 1B or the austenitic steels of group 2C, or modifications thereof, can be used. Tungsten carbide surfacing materials are suitable if the application involves digging loose abrasive material. In general, selection of the most wear-resistant alloy capable of withstanding the impact involved during service is favored.

A program for bucket-tooth maintenance usually requires the use of repointer bars and hard facing. The repointer bar, which consists of a short length of V-section bar, is welded to the worn tooth and thereby restores it to shape. Hard facing prolongs its service life. Figure 14(a) shows a tooth rebuilt with a rolled repointer bar. A length of bar about ¼ in. wider than the width of the tooth is prepared. First, the worn tooth is shaped by means of a gas torch or cutting arc to form a good joint with the bar. Using a manganese steel electrode of group 2C, or other recommended austenitic steel electrode, the bar is tack welded to the tooth with an offset of about ¼ in. from the tooth centerline, leaving a root opening about the size of the electrode being used. Welding is started on the side opposite the offset. As welding proceeds, the centerline of the repointer bar is drawn into line with the tooth centerline; the work is then turned over and welding is started on the opposite side. Welding continues, alternating from side to side, until the joint is fully welded, after which beads are deposited on the sides of the tooth to tie the ends of all weld beads together. Usually at least four teeth are rebuilt at one time, welding on each in turn, to minimize heat buildup.

Cast-to-shape repointers, designed to fit over the ends of worn teeth, are also extensively used. A type that is fillet welded to the worn tooth is shown in Fig. 14(b). Another type, shown in Fig. 14(c), incorporates grooves that are selectively filled with hard facing alloy to maintain the desired tooth shape as it wears. The grooves on the corners and sides of a tooth are filled with hard facing alloy to ensure a straight, sharp edge in service. This design permits deposition of a relatively brittle hard facing alloy on a tough base metal.

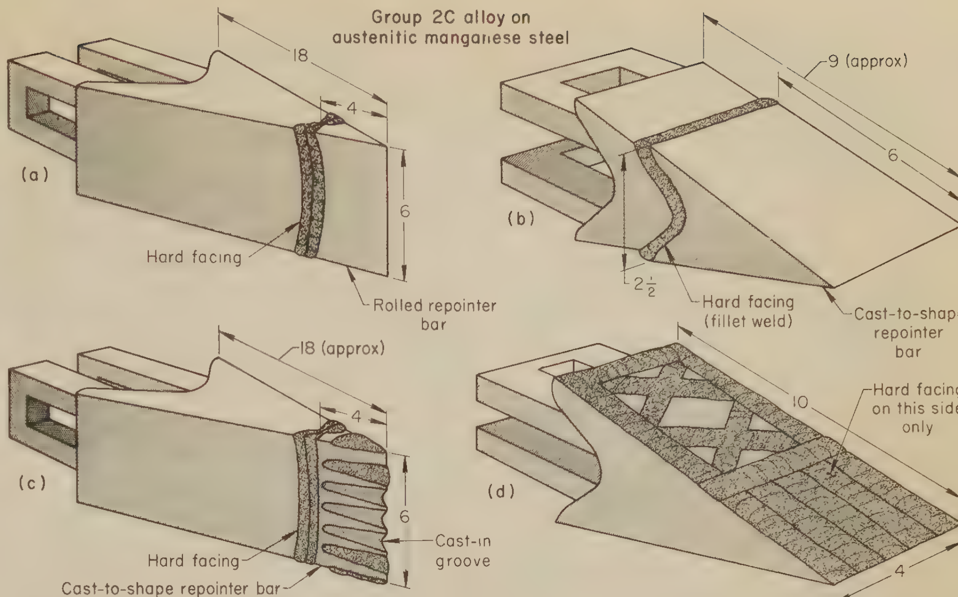


Fig. 14. Manganese steel bucket teeth rebuilt with (a) *rolled repointer bar,* (b) *cast-to-shape repointer bar, and* (c) *grooved cast-to-shape repointer bar.* (d) *Hard faced tooth, new or rebuilt, showing a typical bead pattern on top only to promote self-sharpening (see text).*

Hard facing bead patterns on shovel teeth vary with the type of service anticipated. A pattern commonly used is shown in Fig. 14(d). The tip of the tooth is hard faced with a single continuous hard facing layer on the top only. The crosshatch pattern of stringer beads behind the hard faced tip in Fig. 14(d) is often used to minimize "wash". For service that involves digging of ore or heavy rock, the surfacing beads are laid lengthwise on the tooth — continuously at the tip and in spaced stringers farther back on the tooth. If service involves contact with sand or other fine-particle abrasive material, the beads are laid across the tooth face, parallel to the tip line. Regardless of the bead pattern employed, if it is used only on the top the teeth will be self-sharpening (see the discussion in the preceding section on dragline buckets).

Shielded metal-arc welding is widely used for rebuilding and surfacing bucket teeth. Semiautomatic open-arc welding is also used when the volume of work is great enough to warrant its use.

Pulverizing Hammers. Maintenance of crusher hammers usually requires the use of electrodes of two types — one to rebuild the hammer to within about ³⁄₁₆ in. of the desired dimensions and the other for hard facing, to prolong service life. Austenitic manganese steel crusher hammers are usually rebuilt with group 2C or 2D alloys. If considerable buildup is required, round or square manganese steel segments can be welded on, as shown in Fig. 15(a), to reduce the amount of welding required to restore the hammer to shape. The hard facing alloys most often used are the high-carbon high-chromium alloys of groups 2A and 3A. Hard facing thickness is generally held to two layers. If impact on the hammer is severe, a martensitic steel, similar to some of the lower-carbon grades in group 1B, can be used for the hard facing layers, or an austenitic manganese steel may be used to finish the hammer completely to size.

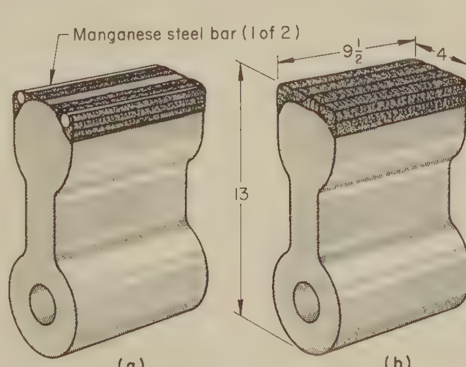
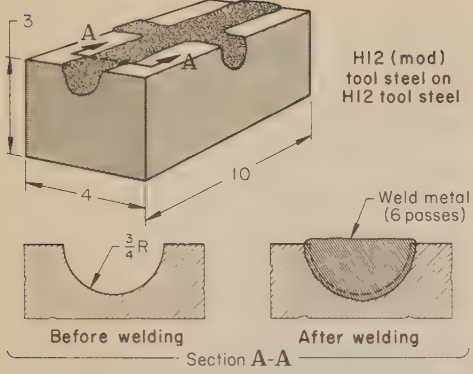


Fig. 15. Rebuilding a crusher hammer by welding and use of manganese steel bars (a), *and hard facing over the buildup* (b)

Hard facing applications on hammers have proved to be economical. In one installation, a new hammer used for crushing limestone lasted about 23 hr; hard facing with a high-chromium alloy increased the service life to more than 60 hr. In other applications, hard facing is known to have extended the service life of old hammers to four to seven times that attainable with new hammers. On the average, about 3 to 5 lb of electrode is required to rebuild and surface an 80-lb hammer. Maintaining a square edge usually limits welding speed. Several hammers are usually rebuilt at one time, skip welding from one hammer to another, so as to minimize heat buildup in the base metal of any hammer. A series of six hammers is often arranged in line, in positions that permit most of the welding to be done in the flat position. In some installations, hammers are rebuilt in place, within the crusher, to eliminate the time lost in dismantling and reassembly. With an efficient setup, rebuilding cost is as little as 25% of the cost of a new hammer. By following proper welding and heat-control procedures, hammers can be rebuilt many times before they are scrapped.



Conditions for Hard Facing by Shielded Metal-Arc Welding

Power supply	300-amp transformer-rectifier
Hard facing alloy	H12 (mod) tool steel(a)
Electrode holder	300 amp, hand held
Electrode diameter	⅛ in.
Welding position	Usually flat
Number of passes	Six; complete filling of groove
Current	110 amp, dcrp
Voltage	22 to 24 v
Preheat and interpass temperature	950 F
Stress-relief treatment	Peening after each pass
Postweld heat treatment	3 hr at 950 F, slow cool

(a) Covered electrodes with the following composition: 0.35 C, 0.30 to 0.40 Mn, 4.75 to 5.25 Cr, 3.00 to 3.50 W, 2.50 to 3.00 Mo, 0.30 to 0.40 V

Fig. 16. Hot upset forging die that was repair hard faced by shielded metal-arc welding (Example 163)

Hard Facing and Weld Repair of Metalworking Tools

Metalworking tools made of tool steel are hard faced and repaired with tool steel, not necessarily of the same composition as the tool. Thus, the compatibility of the base metal and the hard facing alloy, the ability of the facing alloy to perform in service at least as well as the base metal, and the welding characteristics of the two steels are major considerations that influence selection. Because most tool steel hard facing applications are limited to the repair or salvage of damaged or severely worn parts, the economy of hard facing and of repair welding is almost always based on the availability or cost of replacing the original tool.

Welding Processes Used. Shielded metal-arc, gas tungsten-arc, and gas metal-arc welding are widely used in hard facing and weld repair of tools. Manual and semiautomatic methods predominate over automatic methods, because tools are most often repaired individually, rather than in large quantities. Submerged-arc welding is used infrequently, because of its deep arc-penetration characteristic, which is usually detrimental in welding tool steel of high hardenability.

Typical Applications. The examples that follow describe the use of three arc welding processes for hard facing and weld repair of metal-cutting and metal-forming tools. The first example of the series shows how a change in electrode-wire composition had a beneficial effect on the life of repaired dies used in hot upset forging; the other two examples describe the hard facing of shear blades with tool steel.

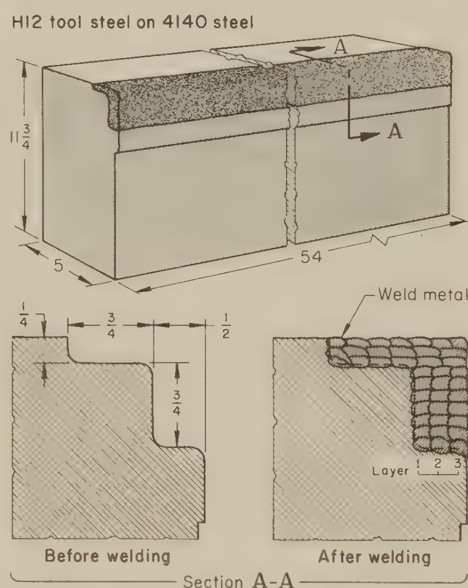
Example 163. Effect of Composition of Hard Facing Alloy on Life of Upset Forging Dies (Fig. 16)

In producing a universal-joint part, the life of a new set of hot upset forging dies made of H12 tool steel was 8000 pieces. When the dies were repaired, using H12 electrode wire of conventional composition and gas metal-arc welding, the dies were usable for an additional 8000 pieces. By changing to a covered H12 electrode with additional alloy content in the coating (total of 3.25% W and 2.75% Mo), the life of repaired dies was increased to between 18,000 and 20,000 pieces. Use of the covered electrode required a change from gas metal-arc to shielded metal-arc welding. The forging die is shown in Fig. 16, and the chemical composition of the covered H12 electrode is given in the accompanying table.

Preparation for welding was similar for both processes. It began with grinding the die impressions to a depth of ⅛ to ¼ in. below the cracks that had resulted from heat checking, to form grooves with a radius of about ¾ in., as shown in Fig. 16. The dies were then preheated in a furnace to 950 F, which was also the interpass temperature during welding. Welding was done in the flat position using reverse-polarity direct current. Six passes were required to fill the grooves. After each pass, the weld bead was stress relieved by peening. After welding was completed, the die block was held at 950 F for 3 hr and cooled slowly. Hardness was Rockwell C 54 to 57. The dies were then machined to size, using the electrical-discharge method.

Additional welding data are given in the table accompanying Fig. 16.

Shear blades used for shearing heavy steel bars at elevated temperatures require a combination of high-temperature impact resistance at the shearing surfaces and high yield strength with good impact and fatigue properties in the body of the blade, in order to perform most efficiently. To achieve this combination of properties at moderate cost, it is often feasible to hard face the edges of a carbon steel or a low-alloy steel blade with a hot work tool steel, provided the welding characteristics of the two steels are compatible. Example 155 describes the hard facing of a carbon steel shear blade by submerged-arc welding. Hard facing of low-alloy steel shear blades by gas metal-arc welding is described in the following example.



Conditions for Gas Metal-Arc Welding

Power supply	600-amp constant-potential rectifier
Hard facing alloy	H12 tool steel
Electrode diameter	0.045 in.
Electrode holder	600 amp, water cooled
Shielding gas	Argon – 1 to 2% oxygen, at 30 cfh
Welding position	Flat
Number of passes	40
Number of layers	Three
Current	250 to 400 amp, dcrp
Voltage	28 to 32 v
Stickout	½ in.
Welding speed	20 to 40 ipm
Preheat	650 F
Postweld heat treatment	3 to 4 hr at 1000 to 1025 F

Fig. 17. Shear blade hard faced using gas metal-arc welding (Example 164)

Example 164. Hard Facing of 4140 Steel Shear Blades With H12 Tool Steel (Fig. 17)

Shear blades made of 4140 steel, for hot shearing heavy steel bars, were hard faced by gas metal-arc welding. Shear-blade dimensions and details of the weld grooves before welding and the layer sequence in welding are shown in Fig. 17.

An electrode capable of depositing a facing equivalent to H12 tool steel was selected, the chemical composition of the electrode being adjusted to compensate for the possible loss of carbon and other alloying elements during welding. Compositions of the electrode metal, the deposited weld metal, and a typical H12 tool steel were as follows:

	C	Cr	W	Mo	V
Electrode metal	0.37	4.95	1.32	1.37	0.46
Weld metal	0.35	4.48	1.30	1.30	0.45
H12 tool steel	0.35	5.00	1.50	1.50	0.40

To begin the operation, the shear-blade blank was thoroughly cleaned and degreased; it was then machined to typical dimensions, as shown in Fig. 17. Before welding, the part was preheated to 650 F. Using a slightly overlapping technique, stringer beads were deposited. Further welding details are provided in the table accompanying Fig. 17. Care was taken to obtain flat beads with low penetration, in order to avoid excessive dilution of the weld metal. To further minimize dilution, the weld metal was deposited in three layers. The blade and the groove faces at the edge were positioned so as to permit flat welding; the first layer was completed on all faces before the second layer was started. Forty passes were required to complete the weld (see Fig. 17). After hard facing, the blades were held at 1000 to 1025 F for 3 to 4 hr, after which the shearing edges were ground to size. This procedure produced cutting edges ranging in hardness from Rockwell C 54 to 56. Blades hard faced in this manner were less expensive and lasted longer in service than unsurfaced tool steel blades.

High-carbon high-alloy tool steels, such as D2 (1.5% C, 12% Cr, 1% Mo), are usually difficult to hard face or repair. Nevertheless, procedures have been developed for welding these tool steels successfully. A procedure for repairing D2 tool steel shear blades, involving two different welding processes, is described in the following example.

Example 165. Repair Welding D2 Tool Steel Shear Blades (Fig. 18)

A welding procedure developed for salvaging tool steel dies, knives, and milling cutters proved successful for repair welding of the D2 shear blade shown in Fig. 18.

Before welding, the worn-out, chipped and cracked areas of the blade, as shown in Fig. 18(a), were ground to obtain a clean, smooth metal surface (Fig. 18b). The blade was then heated in a furnace to 800 F. In the absence of a furnace, slow, even heating with an oxyacetylene torch, using a

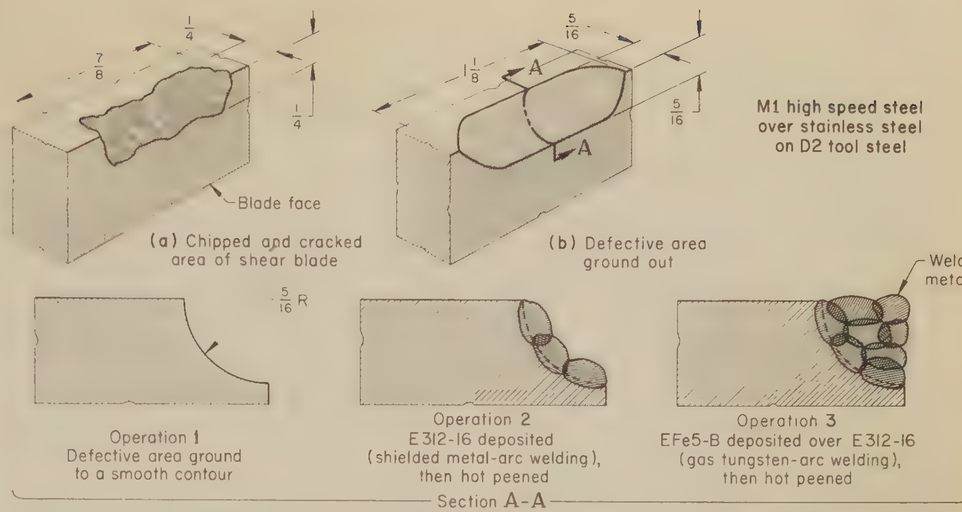
large tip and neutral flame, was satisfactory, the temperature being measured by temperature-indicating crayons.

For repair welding of tool steel blades, choice of a one-step or a two-step procedure depended on the depth of weld metal to be deposited. In this application, the depth of hard facing required did not exceed 3⁄16 in. after finish grinding, and excessive buildup of hard facing alloy would have increased cost, required excessive grinding, and increased the probability of weld cracking. Because the shear blade, after grinding, required a weld approximately 5⁄16 in. deep, an initial buttering pass with a softer, more ductile alloy was necessary. This underlayer was deposited by shielded metal-arc welding, using a flux-covered E312-16 stainless steel electrode, 3⁄32 in. in diameter. Stringer beads about 1 in. long were deposited (Fig. 18, Operation 2). After every 1-in. length of the deposit, the bead was thoroughly ball-peened. Welding and peening were done alternately until about 1⁄8 in. depth remained to be welded. Interpass temperature was maintained within ±100 F of the preheat temperature. Additional data are given in the table accompanying Fig. 18.

With the blade still maintained at interpass temperature, the hard facing was deposited by manual gas tungsten-arc welding, using an EFe5-B (M1 high speed steel) filler metal rod, 1⁄16 in. in diameter, and argon as shielding gas. As before, stringer beads 1 in. long were deposited and immediately peened; it was important to stop peening as soon as the bead cooled to a black heat. It was necessary to deposit a very shallow puddle in order to minimize dilution of the weld metal and consequent decrease in hardenability. To accomplish this, the welder used the technique of playing the arc chiefly on the filler metal.

After depositing sufficient metal, with provision for finish grinding the blade edge to size, the part was allowed to cool to room temperature in still air. Hardness of the deposit after grinding was Rockwell C 58. Additional welding details are given in the table with Fig. 18. Postheat treatment consisted of holding the hard faced blade at 800 F for 1 hr and cooling in air.

A new blade would have cost $35, whereas cost of repairing a blade by the above procedure was about $6 — $1 for material (gas and hard facing alloy) and $5 for labor. In addition, a blade could be salvaged in about 3 to 4 hr elapsed time, whereas a replacement might take weeks.



Welding condition	Underlayer	Hard facing layers
Welding process	Shielded metal-arc	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier with high frequency; time delay for gas and water; foot-operated control	
Electrode	3⁄32-in.-diam E312-16(a)	3⁄32-in.-diam EWTh-2
Electrode holder or torch	Conventional	375 amp, water cooled; gas lens
Hard facing alloy	E312-16	1⁄16-in.-diam EFe5-B(b)
Shielding	Flux cover on electrode	Argon, at 15 cfh
Welding position	Flat and horizontal	Flat and horizontal
Preheat	800 F	800 F
Interpass temperature	700 to 900 F	700 to 900 F
Postweld heat treatment	1 hr at 800 F	1 hr at 800 F
Current	150 to 200 amp, dcrp	100 to 150 amp, dcsp
Arc starting	Conventional	High frequency

(a) Flux covering designation (16) indicates that the electrode can be used with alternating current or reverse-polarity direct current. (b) Same composition as M1 high speed steel.

Fig. 18. Portion of shear blade showing: (a) *chipped and cracked area;* (b) *defective area prepared for repair welding; and sectional views of three successive stages of repair welding* (Example 165)

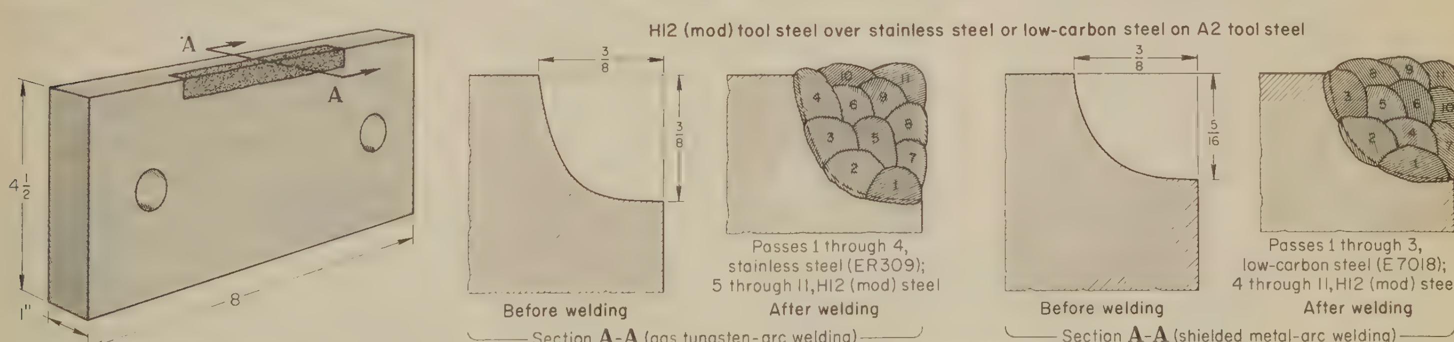
Shear blades made of A2 tool steel also are hard faced and repair welded, using either gas tungsten-arc or shielded metal-arc welding. Procedures for these welding processes, in applying an H11 tool steel repair overlay to an A2 tool steel shear blade, are described in the example that follows.

Example 166. Use of Gas Tungsten-Arc and Shielded Metal-Arc Welding To Make a Surfacing Repair Weld on A2 Tool Steel Shear Blades (Fig. 19)

The welding procedure used to repair damaged cutting edges on A2 tool steel shear blades required close control of conditions affecting heating and cooling of the base metal. A typical blade, for shearing 0.95% C steel sections, is shown in Fig. 19.

Among the problems commonly encountered in welding an air-hardening tool steel such as A2 are the presence of retained austenite in the deposit, and weld cracking. Retained austenite results from rapidly cooling the steel after prolonged heating in the austenitic region, and is characterized by a decrease in hardness after cooling. Cracking is usually caused by abnormal or uneven cooling. To avoid these problems, the following eight precautionary measures were strictly observed while preparing to weld and during the welding operation:

1 In grinding the cracked or broken areas of the damaged blades, precautions were taken against overheating and discoloration of the workpiece surfaces.



Welding condition	Gas tungsten-arc welding	Shielded metal-arc welding
Power supply	300-amp rectifier or 300-amp motor-generator	300-amp motor-generator or rectifier
Electrode	3⁄32-in.-diam EWP	See Hard facing alloy
Hard facing alloy:		
First layer	1⁄16-in.-diam ER309	1⁄8-in.-diam E7018
Subsequent layers	1⁄16 to 3⁄32-in.-diam H12 (mod)(a)	1⁄8-in.-diam H12 (mod)(a)
Shielding	Argon, at 18 to 20 cfh	Flux cover on electrode

Welding condition	Gas tungsten-arc welding	Shielded metal-arc welding
Welding position	Flat	Flat
Preheat	800 F	800 F
Interpass temperature	750 to 950 F	750 to 950 F
Postweld heat treatment	1 hr at 900 F	1 hr at 900 F
Current: First layer	95 to 115 amp, dcsp	120 to 125 amp, dcrp
Subsequent layers	95 to 115 amp, dcsp	110 to 125 amp, dcrp
Voltage	22 to 24 v	21 to 23 v
Welding speed	3 to 5 ipm	5 to 7 ipm

(a) Composition: 0.75 to 1.00 C, 0.40 to 0.60 Mn, 5.50 to 5.75 Cr, 1.00 to 1.10 W, 1.75 to 2.00 Mo, 0.90 to 1.00 V

Fig. 19. Shear blade with edge hard faced with modified H12 tool steel, using gas tungsten-arc or shielded metal-arc welding (Example 166)

2 All welding was done indoors, in a draft-free environment.
3 Workpieces were preheated to 800 F in a furnace or by gas torch. Heating was even and uniform. The temperature of the workpiece was checked repeatedly with temperature-indicating crayons.
4 The ground connection was clamped securely, to ensure the absence of hardened arc spots on the workpiece and variations in welding current.
5 Weld bead deposits did not exceed 3 in. in length, which enabled them to retain the heat required to obtain good results from peening.
6 Immediately following deposition of each 3 in. of bead, the red-hot bead was lightly peened with a ball-peen hammer to prevent stress concentration and cracking; the deposit was then wire brushed.
7 The interpass temperature was checked after every third deposit and was kept in the range of 750 to 950 F.
8 Each bead was deposited as a straight stringer bead, without weaving or oscillation of the torch during welding.

Gas tungsten-arc welding was started by first depositing one complete layer of weld-metal beads, using 1/16-in.-diam ER309 stainless steel filler metal (25% Ni, 12% Cr). This buttering layer provided a ductile buffer between the hardened base metal and the subsequent passes of hardenable weld metal. (Either ER308 or ER316-ELC filler metal could be substituted for ER309.) The remaining passes were made with a rod of proprietary composition (see the table accompanying Fig. 19) equivalent to a modified H12 tool steel.

Machine settings and other welding conditions are given in the table with Fig. 19. Small, straight stringer beads made with low heat input and in the sequence shown in Fig. 19 were essential for the success of the operation.

After hard facing was completed, the workpiece was placed in a furnace previously heated to 200 F. Furnace temperature was then increased to 900 F, so that both the workpiece and the furnace were heated at the same rate. Parts were held at 900 F for 1 hr and were then removed and allowed to cool in a draft-free area. They were not covered at any time.

Hardness readings taken after repaired edges were ground to size and shape ranged from Rockwell C 57 to 60. This compared favorably with the base-metal hardness of Rockwell C 56 to 58.

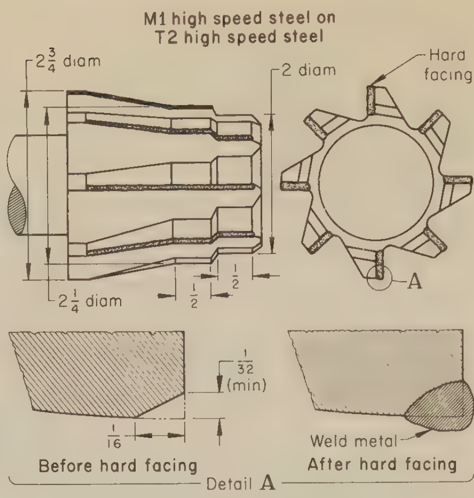
Shielded metal-arc welding was also successfully used for repair welding the damaged cutting edges of A2 tool steel shear blades, using the same procedural sequence as for gas tungsten-arc welding, except for the filler metals used and the details of operation. The eight precautionary measures listed above were strictly adhered to.

The initial layer (beads 1 to 3), as shown in Fig. 19 (right), was deposited using a 1/8-in.-diam E7018 low-hydrogen iron-powder electrode. The low hydrogen minimized the possibility of underbead cracking, and the iron powder favored use of high welding speed, which gave relatively low penetration. These beads formed a buffer layer of relatively ductile steel between the base metal and the subsequent layers of hard facing metal. Beads 4 through 11 were deposited with a 1/8-in.-diam modified H12 tool steel electrode (see the table with Fig. 19 for the composition).

Although the number of beads per layer could vary, depending on the size of the groove to be filled, the sequence pattern shown in Fig. 19 (right) was essential to the success of the operation.

Machine settings and other conditions for both types of weld deposit are given in the table with Fig. 19. The postheating procedure was the same as that employed after gas tungsten-arc welding.

High speed steels, which are extensively used for metal-cutting tools, are difficult to weld because of their high carbon and alloy contents. Weld repair of these tools is sometimes economically attractive, as in the following example,



Manual Gas Tungsten-Arc Welding

Power supply	300-amp transformer-rectifier; time delay for gas and water; foot-operated control
Electrode	3/32-in.-diam EWTh-2
Torch	375 amp, water cooled; with gas lens
Hard facing alloy	1/16-in.-diam RFe5-B(a)
Shielding gas	Argon, at 15 cfh
Welding position	Flat
Preheat and interpass temperature	900 F
Postweld heat treatment	1 to 2 hr at 1000 F(b)
Current	100 to 150 amp, dcsp
Voltage	Not controlled
Arc starting	High frequency

(a) Same composition as M1 high speed steel; heat treatable, if annealed, using M1 heat treating specifications. (b) Furnace cool or, if heated with a torch, bury in lime for cooling.

Fig. 20. Stepped reamer that was salvaged by hard facing, using manual gas tungsten-arc welding (Example 167)

which describes the repair welding procedure used in one application for salvaging high speed steel reamers.

Example 167. Repairing Worn Cutting Edges on High Speed Steel Reamers (Fig. 20)

The cutting edges of high speed steel reamers used for finishing holes in malleable iron castings were rapidly worn down by the action of sand inclusions and hard spots in the castings. The worn cutting edges could have been salvaged by cutting a portion from the front end of the reamer and regrinding all surfaces to size, but this operation would have been time-consuming and expensive. Instead, when wear exceeded tolerance limits, reamers were salvaged by hard facing the flutes, using manual gas tungsten-arc welding. The small, confined heat source obtained in the process permitted accurate placement of beads without the need for prior annealing of the reamer.

The front end of a high speed steel reamer with hard faced cutting edges is shown in Fig. 20. Preparation for welding consisted in grinding each cutting edge to a depth of not less than 1/32 in. below the original cutting surface (see sectional detail in Fig. 20). The ground edges were inspected to make certain that no cracks or partially separated chips remained. Oil and grease were removed with detergent, and oxide discoloration was removed with an emery cloth. The tool was preheated slowly to 900 F in a gas furnace provided with a neutral atmosphere. When a furnace was not available, an oxyacetylene torch was used for preheating; a neutral flame from a large tip was played over the tool surfaces to distribute the heat evenly; temperature was measured with a 900 F indicating crayon.

After preheating, a stringer bead was deposited along the full length of the prepared edge of each flute, starting at an end, using filler metals of 1/16-in. diameter and of composition comparable to that of M1 high speed steel. A power supply of 300-amp capacity was used to furnish straight-polarity direct current (electrode negative). Time delay for preflow and postflow argon and water circulation, and continuous high-frequency current for arc starting and stabilization were provided.

Current between 100 and 150 amp was used for welding and was controlled by a pedal. For details of machine settings and other welding conditions, see the table accompanying Fig. 20.

The welding technique used was important. The welder had to maintain a short arc with the heat directed mainly on the filler-metal rod, so as to create a shallow weld puddle. Dilution with base metal had to be held to a minimum to avoid decreasing the hardenability of the deposit. By uninterrupted operation, it was possible to use the heat input of welding to maintain interpass temperature at the preheat level. After welding, the tool was cooled to room temperature in a draft-free area.

As a postweld treatment, the tool was heated slowly to 1000 F and held at that temperature for 1 to 2 hr. When a furnace was not available, the tool was heated to 1000 F with a torch and buried in lime for at least 6 hr. After cooling, the tool was reground and returned to service.

The salvaging operation was repeated successfully several times on the same tool. Actual savings on reamers of different types varied with the cost of replacement. The stepped reamer of T2 steel, described here, was repaired at a cost of approximately $15, which was about one-fifth of its replacement cost. In general, savings of 50% or more could be realized.

Other Examples of Surfacing in This Volume

Example	Subject of example
62	ASTM A235, class C1, 15½-in. OD by 31⅝ in. long, surfaced with ER309
63	Valve seats in steam chest made of Cr-Mo steel surfaced with ER410
64	Groove in ASTM A36 steel sheave surfaced with cored wire; deposit similar in composition to type 309 stainless steel
91	ASTM A285 steel flange surfaced with ER308 stainless steel
92	Bearing surfaces on low-carbon steel part faced with ECuAl (bronze) wire by gas metal-arc welding
93	Inner surface of 16-in.-ID 4140 steel hub faced with ECuAl-B for resistance to wear and corrosion
94	Large-diameter low-carbon steel vessels faced with E310 stainless steel for corrosion resistance
194	1030 cast steel rotor surface rebuilt with special-composition wire by submerged-arc welding
195	ASTM A266, class 2, forged tube sheet faced with low-carbon steel to increase ductility of fillet welds at joints with tubes
207	Cr-Ni-Mo steel shaft (25-in. diam) surfaced by submerged-arc welding with Cr-Mo electrode wire
219	ASTM A302, grade B (Mn-Mo), steel cylinder (92-in. ID) faced with Inconel 600
234	Ductile iron casting built up using shielded metal-arc welding with an electrode having a nickel content higher than that of ENiFe-CI
316	Aluminum alloy 355-T6 casting surfaced for correction of a machining error, using gas tungsten-arc welding with ER4043 filler wire
345	Defect in a magnesium alloy AZ91C-T4 casting repaired by gas tungsten-arc welding with ERAZ91C wire
346	Defect in a magnesium alloy AZ91C-T6 casting repaired by gas tungsten-arc welding with ERAZ92A wire
348	Correction of a machining error in a magnesium alloy AZ92A-T6 casting by gas tungsten-arc surface welding with AZ92A wire
349	Magnesium alloy AZ92A-T6 surfaced to fill machining scratches
351	Addition of a 1-in.-diam boss to a magnesium alloy EZ33A casting, using gas tungsten-arc surface welding and EZ33A wire
531-543	Hard facing by oxyacetylene welding

Stud Welding

*By the ASM Committee on Flash, Friction and Stud Welding**

STUD WELDING is an arc welding process in which the contact surfaces of a stud, or similar fastener, and a workpiece are heated and melted by an arc drawn between them, and then are brought together ("plunged") rapidly under pressure to form a weld. Arc initiation, arc time, and plunging are controlled automatically.

The two basic methods of stud welding are known as arc stud welding and capacitor-discharge stud welding. Both methods involve direct current and arcing. For arc stud welding, a motor-generator, a transformer-rectifier, or a storage battery is the power supply. The power supply for capacitor-discharge stud welding is a low-voltage electrostatic storage system, and the arc is produced by a rapid discharge of stored electrical energy. A welding-current controller and a welding tool, or gun (stud gun), complete the necessary welding equipment for both methods of stud welding. In the arc method, a ceramic ferrule is generally used to retain the molten weld metal.

In both methods, the stud, or fastener, serves as the electrode; the gun is the electrode holder. Flux is generally used for arc stud welding of ferrous alloys; it provides cleaning action and a protective atmosphere. When used, flux is on or within the end of the stud. The arc time for capacitor-discharge welding is so short that flux is not needed. A shielding gas is usually introduced around the stud in welding nonferrous metals by both methods.

Generally, in arc stud welding, straight polarity (stud negative and workpiece positive) is used for ferrous alloys and reverse polarity for nonferrous alloys. Straight polarity is used in capacitor-discharge stud welding.

The procedure used to initiate the arc and to control the welding cycle and current varies with the method.

Stud welding is similar to percussion welding (see page 177).

Process Capabilities and Limitations

Stud welding is a rapid process. Welding time, which depends on the method and on the diameter of the stud, varies from 1 to 12 milliseconds for the capacitor-discharge method and from 0.10 sec to slightly more than 1 sec for arc stud welding. Melt-through and distortion are at a minimum in both methods. Maximum strength of the fastener is developed when the diameter of the weld base of the stud is not more than three times the thickness of the base metal.

Studs can be welded in places that are not readily accessible when other welding methods are used, and the welded area need not be in view of the operator. (In Example 171, a stud was inserted through the cover sheet and core of a honeycomb panel and was capacitor-discharge welded to the inner surface of the lower sheet.)

The shank of a stud or other weld fastener can be of any size, shape or type that can be gripped in the stud holder. Length can vary from 5⁄32 in. for a special capacitor-discharge application to several feet.

Usually, the weld base (the end of the stud or other weld fastener that is to be welded) is round for both processes. However, square and rectangular-base studs can be welded by the arc method. Studs 1⁄16 to 1¼ in. in diameter and rectangular welding pins ⅛ by ⅜ in. to ¼ by 1¼ in. have been welded. Small sheet-metal cups have been welded to workpieces using the capacitor-discharge method.

Suitable stud and base metals are the same as those welded by other arc welding processes. The metals most frequently stud welded are low-carbon steel, low-alloy high-strength steel, austenitic stainless steel, aluminum alloys, and some copper alloys. Alloy steels, magnesium alloys, titanium alloys, zirconium alloys, and zinc alloy die castings also have been stud welded.

Welding of various base metals and typical combinations of base metal and stud metal are described in the section on Metals Welded, on page 174.

Stud welded fasteners can replace fasteners normally secured by riveting, drilling and tapping, manual arc welding, resistance welding, or brazing. The studs are attached to only one side of the workpiece.

Applications. Stud welding is most often used to end-weld a stud or other fastener to a plane surface. The arc method can be used also to weld fasteners to curved surfaces such as pipe or to inside and outside corners of structural members.

Some typical applications of stud welding are: attaching wood floors to steel decks or framework; securing special linings in tanks, boxcars and other containers; studding boiler tubes; assembling electric panels; securing inspection covers of various kinds; securing trim moldings and emblems to automobiles; securing air, water, hydraulic, and electrical lines to buildings, vehicles and large appliances; welding shear connectors and concrete anchors to structures; and securing handles and feet to small appliances.

The process lends itself to automatic feeding of studs to the gun for welding at a rate of 45 per minute or more. Accuracy of location depends on product design and the process equipment.

Limitations are as follows:

1. Studs must be of a size and shape that permit chucking, and the cross-sectional area of the weld base of the stud must be within the range of the welding equipment.
2. Studs for arc stud welding usually must permit the use of a ceramic ferrule, or arc shield, around the weld base. Also, the weld base often must accommodate flux.
3. Studs for capacitor-discharge stud welding sometimes require a carefully designed, close-tolerance projection on the weld base, the function of which is to make initial contact with the workpiece to initiate the arc.
4. Areas to be welded must be clean and free from paint, scale, rust, grease, oil, dirt, zinc plating, or cadmium plating. Aluminum surfaces require oxide removal if badly oxidized.
5. Only one end of the stud can be welded to the workpiece.
6. Studs are secured to only one side of the workpiece. If a stud is required on both sides, a second stud must be welded to the opposite side.

Stud Welding Guns

The gun holds the stud in position while the welding current is applied; it can be hand held or bench mounted.

A gun for capacitor-discharge stud welding is shown in Fig. 1. Guns for arc stud welding are similar, except that provision is made for a ferrule holder or, when welding aluminum studs, a gas-adapter foot assembly.

Process Selection

Table 1 compares the applicability of arc and capacitor-discharge stud welding for various base metals, base-metal thicknesses, stud metals, and weld-base shapes and sizes. A comparison of the capabilities of arc and capacitor-dis-

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Elton S. Gamble, Engineering Specialist, Olin Metals Research Center, Olin Corp. (formerly with American Machine & Foundry Co.); Robert J. Gasser, Manager, Resistance Welding Systems, Sciaky Bros., Inc.; John C. Jenkins, Manager, Application Development Dept., Nelson Stud Welding Co.; Ivar W. Johnson (retired), Metallurgist, Knolls Atomic Power Laboratory, General Electric Co.; C. D. Loyd, Supervisor, Materials Div., Engineering General Office, Caterpillar Tractor Co.; G. W. Reeder, Chief Metallurgist, American Welding & Manufacturing Co.; W. C. Rudd, Director, AMF Thermatool, Inc.

A. L. Williams, Manager of Engineering, Welders and Presses, Wean Industries, Inc.; W. F. Williams, Equipment Engineer, Buick Motor Div., General Motors Corp.; A. C. Young, Pressure Weld Engineer, Power Transmission Div., General Electric Co.

Most of the examples presented in this article were contributed by members of other Metals Handbook welding committees.

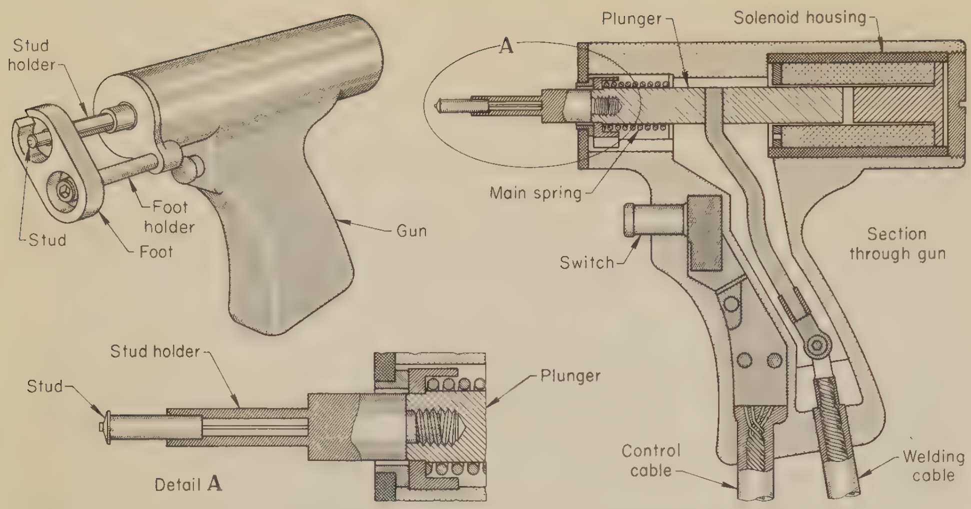


Fig. 1. Gun for capacitor-discharge stud welding. Arc stud welding guns are similar but have a ferrule holder in the foot.

Table 1. Applicability of Arc and Capacitor-Discharge Stud Welding

Item	Arc stud welding	Capacitor-discharge stud welding: Initial-contact; initial-gap	Capacitor-discharge stud welding: Drawn-arc
Base Metal			
Carbon steel	A	A	A
Alloy steel	B	A	C
Stainless steel	A	A	A
Aluminum alloys	B	A	A
Copper alloys	C	A	A
Base-Metal Thickness			
Under 0.015 in.	D	A	B
0.015 to 0.062 in.	C	A	A
0.062 to 0.125 in.	B	A	A
Over 0.125 in.	A	B	A
Stud Metal			
Carbon steel	A	A	A
Alloy steel	B	C	C
Stainless steel	A	A	A
Aluminum alloys	B	A	A
Copper alloys	C	A	A
Weld-Base Shape			
Round	A	A	A
Square	A	C	C
Rectangular	A	C	C
Irregular	A	C	C
Weld-Base Diameter or Area			
1/16 to 1/8-in. diam	D	A	A
1/8 to 1/4-in. diam	C	A	A
1/4 to 1/2-in. diam	A	C	C
1/2 to 1-in. diam	A	D	D
Up to 0.05 sq in.(a)	C	A	A
Over 0.05 sq in.(a)	A	D	D

A — Applicable without special techniques and equipment
B — Applicable with special techniques or on specific applications that justify preliminary trials or testing to develop welding procedure and technique
C — Limited applicability
D — Not recommended; welding methods not developed at this time.

(a) Data apply primarily to round weld bases, but in arc stud welding, they apply to square and rectangular-shape bases.

charge stud welding when attaching aluminum alloy studs to Teflon-coated and natural-finish aluminum alloys is given in Table 2.

The following considerations are pertinent to process selection:

1 **Base Metal.** Low-carbon steel and austenitic stainless steel are weldable by both the arc and the capacitor-discharge methods. Some non-heat-treatable aluminum alloys can be welded by the arc method, but most such alloys and alloys 6061 and 6063 are welded by the capacitor-discharge method. Copper, brass and galvanized steel sheet usually are welded by the capacitor-discharge method only.

2 **Base-Metal Thickness.** If the base metal is less than 0.036 in. thick, the capacitor-discharge method should be used. (Tables 1 and 2 show minimum base-metal thickness for various stud diameters, for arc and capacitor-discharge welding.)

3 **Weld-Base Shape.** The weld base for capacitor-discharge stud welding is nearly always round. Square or rectangular pins, collared studs or split pins are all arc stud welded.

4 **Weld-Base Diameter.** For diameters greater than 3/8 in., arc stud welding must be used. The diameter range for capacitor-discharge stud welding is 1/16 to 3/8 in.

Arc stud welding results in a much larger heat-affected zone than the capacitor-discharge method. Also, capacitor-discharge welding results in a very small fillet; arc stud welding, in a relatively large fillet.

The weld-fillet size in arc stud welding is controlled by the ceramic ferrule, which serves as a dam to contain the molten metal. Dimensions of the weld fillet usually must be considered in the design of parts through which the studs pass. In Example 173, holes in the mating part were increased from 9/16 to 5/8 in. in diameter, to clear the fillet.

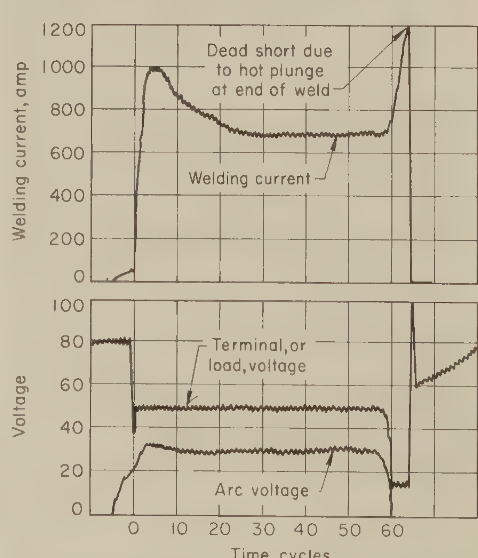


Fig. 2. Oscillograph traces of current and voltage during arc stud welding for 65 cycles (based on 60 cycles per second)

Arc Stud Welding

Arc stud welding is used to best advantage when the base metal is thick enough to enable the weld to be made without burn-through and the full strength of the welded stud to be developed. For low-carbon steel, the weld-base diameter of the stud should be no more than three times the base-metal thickness.

Rust-coated and scale-coated surfaces can be welded if the weld area is cleaned with a wire brush, or if the scale is broken with a centerpunch so that the arc can be established at the centerpunch mark. The weld area on oiled, painted and plated surfaces should be cleaned to ensure sound welds. Excessive oxide must be removed from the weld areas on aluminum workpieces.

Power Supply. A transformer-rectifier, a motor-generator, or a storage battery can be used to supply the direct-current power needed for arc stud welding. Some of the power-supply units made for other arc welding processes are satisfactory, but equipment designed specifically for arc stud welding is recommended, for greater efficiency and the most appropriate voltage and amperage characteristics.

The power needed for welding the larger-diameter studs frequently is obtained by connecting two or more power-supply units in parallel.

Characteristics of power supply for arc stud welding include:

1 **A high open-circuit terminal voltage** (the voltage at the welding terminals when welding is not taking place) of 60 to 100 volts. Control components, such as the timer, relay and contactor, are designed to operate in this voltage range. A high open-circuit voltage energizes the control components efficiently; if the open-circuit voltage is below 55 volts, operation of the control unit may become erratic.

2 **Drooping volt-ampere characteristic** is preferred, because it provides a relatively high open-circuit voltage that is above the arc voltage, and because it helps to establish and maintain the arc. Also, it provides a more stable arc. The momentary increase in current caused by the stud shorting out the welding arc when the stud is plunged into the base metal at the end of the weld cycle is relatively small.

The constant-voltage curve is flat. Also, most constant-voltage machines have a low open-circuit voltage, generally about 40 volts. Because the volt-ampere curve is flat, current for a dead-short condition is, theoretically, unlimited. This means that whenever drops of metal short out the arc, current is very high, causing the arc to blast and be unstable for stud welding. Thus, constant-voltage machines are not usually employed for stud welding, because low open-circuit voltage results in erratic operation or in nonoperation of the control units, and the flat volt-ampere curve causes an unstable arc. Constant-voltage machines can be used, however, if a special control unit that operates on 115-volt alternating current is employed, but arc characteristics are not ideal.

3 **Rapid Current Rise.** The welding current should rise to its peak value in

less than two cycles, or approximately 32 milliseconds. If the current rises too slowly, a stable arc will not be established. Figure 2 (top) shows a typical current oscillograph trace for a stud weld. The welding current rises steeply to a peak of 1000 amp, then drops to 700 amp as the machine slows down.

4 **High Short-Time Current Output.** Current output required is three to six times that required for other manual and automatic welding methods, and the duty cycle is only 5 to 15%, instead of 60 to 100%.

Terminal Voltage and Arc Voltage. Figure 2 (bottom) shows a typical voltage oscillograph trace for a stud weld. (The traces in Fig. 2 were made using a motor-generator set; the voltage characteristics of other types of direct-current power units would be similar.) The voltage at the terminals of the machine was 80 volts, until welding current was drawn. When welding current started to flow, the terminal voltage dropped to 50 volts. After the weld was completed, the terminal voltage dropped to less than 20 volts, then increased rapidly to a very high value because of the inductance in the machine, and then dropped to slightly below the normal open-circuit voltage. The voltage then slowly increased to its original open-circuit value, as the machine regained full speed.

The lower voltage trace in Fig. 2 (bottom) is the arc voltage, which depends on arc length. It is usually 30 to 35 volts. The trace shows that there was arc voltage before the welding current started to flow. This is pilot arc voltage. The difference between load voltage and arc voltage is a result of voltage drop in the cables, connectors, ground connection, and contactor. In Fig. 2, there was a 20-volt drop in the circuit between the machine and the welding arc.

Output Rating vs Stud Diameter. A 400-amp NEMA-rated direct-current welding machine is used for studs up to 7⁄16 in. in diameter. A 600-amp machine will weld studs of ½-in. diameter. Two 400-amp machines connected in parallel are needed for ⅝-in.-diam studs, and two 600-amp machines connected in parallel are needed for ¾-in.-diam studs. A 1-in.-diam stud requires a 2000-amp machine.

In some applications, studs welded by a machine with a transformer-rectifier would have to be 1⁄16 in. in diameter smaller than studs welded by a motor-generator machine of the same rating.

Cables. The size and length of welding cables and ground cables affect the power available at the welding gun. Figure 3 shows that, for a given length of cable, the welding current can be increased about 10% by using a cable of the next larger diameter. Also, for a given size of cable, the current at the gun decreases as the length of the cable is increased.

Studs are specially manufactured, and the weld end is flux-loaded, when necessary, and equipped with a porcelain or ceramic ferrule. The ferrule shields and controls the welding arc, concentrates the heat of the arc in the weld area, and also acts as a dam to control the flow of the molten metal and to restrict it to the weld area.

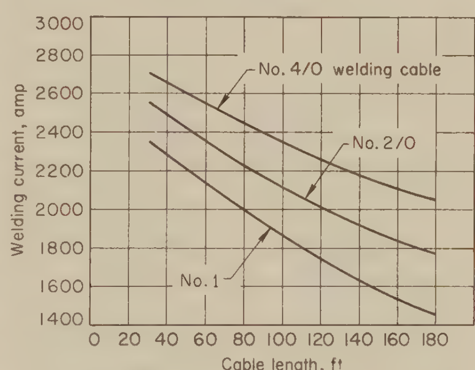
Table 2. Comparison of Arc and Capacitor-Discharge Stud Welding of Aluminum Alloy Studs to Teflon-Coated and Natural-Finish Aluminum Alloy Base Metal

Item	Arc stud welding	Capacitor-discharge stud welding: Initial-contact; initial-gap	Capacitor-discharge stud welding: Drawn-arc
Weld-base diameter, in., max	0.375	0.375	0.375
Shielding gas, cu ft per weld	0.008	None	0.008
Minimum base-metal thickness, in.:			
Teflon-coated aluminum(a)			
0.250-in.-diam weld base	0.070	0.030	0.040
0.312-in.-diam weld base	0.080	0.040	0.060
0.375-in.-diam weld base	0.100	0.040	0.060
Natural-finish aluminum(b)			
0.250-in.-diam weld base	0.060	0.030	0.030
0.312-in.-diam weld base	0.060	0.030	0.040
0.375-in.-diam weld base	0.080	0.030	0.050
Position of stud on base metal:			
Angle from perpendicular, max(c)	10°	0°	2°
Angle with special chuck, max(d)	25°	0°	2°
Weld quality, rough or textured surface	Excellent	Fair	Excellent

(a) Without damaging Teflon coating. (b) Without damaging finish. (c) Angle at which stud can be off perpendicular to surface of base metal and produce a good weld. (d) Angle to gun motion.

The flux acts as an arc stabilizer, and as a deoxidizing agent when steel is welded. It is held at the center of the weld base within 0.010 in. of true position. Except for special applications, flux is not needed for studs less than ¼ in. in diameter.

Studs come in various styles, lengths and diameters (or widths and thicknesses), and compositions. They are frequently custom designed.



Data were determined by welding studs with a special 2000-amp machine that was operated at the highest setting. Cable length is combined length of welding cable and ground cable. Amperage is average for 60 cycles or 1 second.

Fig. 3. Effect of cable size and length on welding current that is available at the welding gun

Because a stud must extend through the ferrule an amount equal to the burn-off (⅛ to 3⁄16 in., depending on the diameter), minimum stud length usually is about ¾ in. When automatic feeding systems are used, maximum length is about 1 in. Amount of burn-off must be considered when the finished length of the stud is important.

The weld base of a stud can be larger or smaller than the body, and can be of any shape. Rectangular fasteners should have a width-to-thickness ratio no greater than 5 to 1. Fasteners having a weld base with a greater ratio weld inconsistently and are not recommended.

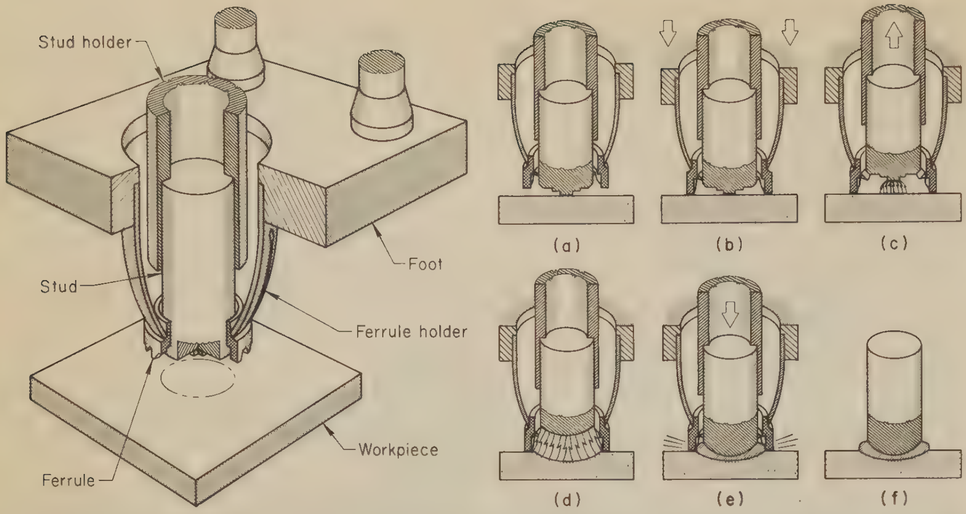
On round studs, the weld-base diameter generally should be no more than five times the base-metal thickness, but a ratio of about 3 to 1 is needed for making a weld that is stronger than the stud and causes no burn-through or excessive distortion of the base metal. The minimum base-metal thicknesses and starting conditions for arc stud welding of low-carbon steel and aluminum alloys are given in Table 3.

The end of a stud with a round weld base is convex or conical. Rectangular fasteners have tapered tips, the apex being at the center of the width dimension. This shape helps to initiate the arc at the center of the stud, permitting the arc to spread equally along the surface to be heated. Also, if the

Table 3. Minimum Base-Metal Thickness and Starting Conditions for Arc Stud Welding of Low-Carbon Steel and Aluminum Alloys(a)

Weld-base diameter, in.	Minimum base-metal thickness, in.: Without backing	Minimum base-metal thickness, in.: With backing	Stud travel, in.: Lift	Stud travel, in.: Plunge	Weld time, cycles(b)	Welding current, amp(c)	Shielding-gas flow, cfh(d)
Low-Carbon Steel							
0.187	0.036	...	0.06	0.12	7	300	...
0.250	0.048	...	0.06	0.12	10	425	...
0.312	0.060	...	0.06	0.12	15	500	...
0.375	0.075	...	0.06	0.12	20	550	...
0.437	0.090	...	0.06	0.12	25	675	...
0.500	0.120	...	0.09	0.15	30	800	...
0.625	0.148	...	0.09	0.15	40	1200	...
0.750	0.187	...	0.12	0.18	50	1600	...
0.875	0.250	...	0.12	0.18	60	1800	...
1.000	0.375	...	0.12	0.18	70	2000	...
Aluminum Alloys							
0.250	0.125	0.125	0.09	0.12	15	250	15
0.312	0.125	0.125	0.09	0.12	20	370	15
0.375	0.187	0.187	0.09	0.12	25	540	20
0.437	0.250	0.187	0.09	0.18	30	570	20
0.500	0.250	0.187	0.09	0.18	43	640	20

(a) These are starting conditions and must be adjusted to welding conditions and strength requirements. (b) Based on 60 cycles per second. (c) Minimum of 65 volts open-circuit voltage recommended. Amperage is actual and does not necessarily correspond to power supply dial settings. When stainless steel studs are welded, amperage is increased 10%. (d) Shielding gas not needed for stud welding steel. Generally, argon is used for stud welding aluminum alloys.



(*a*) First, the stud is located on the workpiece. (*b*) Force is applied so that the spring within the gun is compressed until the ferrule is seated firmly on the workpiece. (*c*) When the welding current is turned on, the solenoid in the welding gun is energized, the stud is automatically lifted, and an arc between the face of the stud and the workpiece is initiated. (*d*) With the stud in the lifted position, arcing spreads across the face of the stud and the heat of the arc melts an area on the workpiece and produces a weld puddle under the stud, and also melts a small portion of the face of the stud. (*e*) When the welding current is stopped, the solenoid is de-energized and the face of the stud is plunged, by spring pressure, into the weld puddle. (*f*) Finished weld; note shape of fillet formed by the ferrule.

Fig. 4. Sequence of steps in arc stud welding

stud is held a few degrees from perpendicular to the surface of the base metal, initial contact still will be made and the arc will be drawn at the center of the stud, instead of on the periphery.

Fasteners are sometimes coated with cadmium, zinc or other plating materials. Plating must be removed from the weld base of all studs more than $\frac{3}{16}$ in. in diameter, to prevent contamination of the weld.

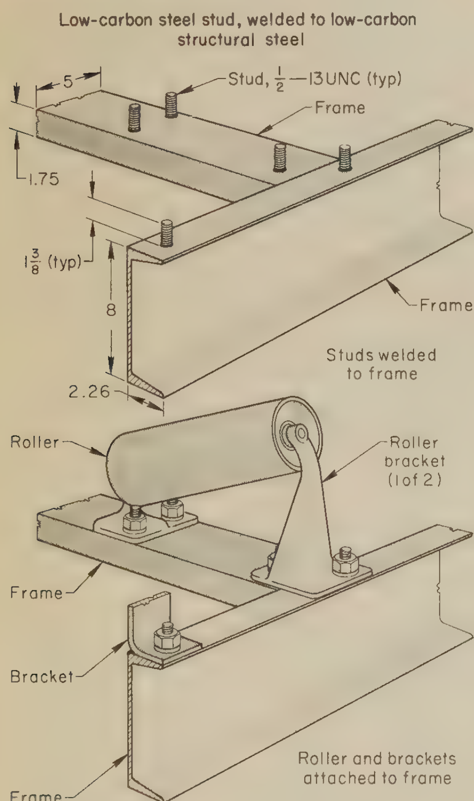


Fig. 5. Brackets fastened to a belt-loader frame made of heavy structural sections, using studs rather than through-bolts (Example 168)

Stud Location. The method of locating a stud depends on the stud and the accuracy required. For manual welding, centerpunch marks or scribed lines are used. The tip of the stud or the flux is placed on these marks. Where greater accuracy is needed, a template with holes of slightly larger diameter than the ferrule diameter is used. Spacers about $\frac{3}{32}$ in. thick must be inserted between the template and the workpiece to allow gases generated during welding to escape. (Example 170 on page 172 describes the use of a locating template.)

In production setups, the welding tool can be bench mounted and the studs located on the workpiece by means of fixtures or indexing tables.

Procedure. The stud is placed in the stud holder of the welding gun, and the ferrule is placed in the ferrule holder, which is adjusted during setup so that the stud will extend $\frac{1}{8}$ to $\frac{3}{16}$ in. beyond the ferrule. Figure 4 shows the steps in arc stud welding.

A controlling device limits arc time (the number of cycles the arc is allowed to burn), according to a predetermined setting. At the end of the arcing period, the timing device shuts off the welding current, de-energizes the solenoid, and plunges the end of the stud into the small volume of molten metal (the weld puddle, or weld pool) in the base metal. When the weld puddle solidifies, the weld is complete. Because the weld solidifies almost instantly, the gun can be moved to the next weld position without delay. The welding gun is then removed and the ferrule is broken off. A shielding gas is sometimes used when nonferrous alloys are being stud welded.

The duration of the welding cycle depends on the weld-base diameter, or cross-sectional area, of the stud and on the metals being joined. Table 3 lists typical welding conditions for low-carbon steel studs with weld-base diameters of 0.187 ($\frac{3}{16}$) to 1 in. and for aluminum alloy studs 0.250 to 0.500 in. in diameter.

Studs can be welded in the flat, overhead or vertical position. The highest weld quality is produced in the flat and overhead positions.

Examples of Practice. Often, product appearance is improved and assembly costs are reduced by using stud welding. Studs are surface mounted to one side of a workpiece without holes or reverse-side marking. In the following example, product appearance was improved by eliminating bolt heads, and assembly time was reduced because of elimination of the drilling operation.

Example 168. Change From Bolting to Stud Welding for Attachment of Conveyor Support Brackets to a Frame (Fig. 5)

End-welded studs were used for attaching conveyor support brackets to the frame of a mobile belt loader, as shown in Fig. 5. The studs, $1\frac{3}{8}$ in. long, with $\frac{1}{2}$–13 UNC threads, were made of low-carbon steel, and the frame was made of channel-shape structural steel sections. A portable arc stud welding gun was used. Weld time per stud was about 30 cycles, and welding current was about 800 amp.

A total of 92 studs was required for attaching the brackets, which had originally been attached by bolting. Changing to studs eliminated drilling of these holes, the through-bolts, and the tapered washers that were used under the bolt heads, and assembly was faster, because fastening was from one side only and it was not necessary to hold the bolt heads while the nuts were being tightened. Stud welding also eliminated bolt heads showing on the outer surfaces and simplified maintenance.

Hood covers and hydraulic hose clamps were also attached to the loader, using an additional 91 studs, which were $\frac{5}{16}$ and $\frac{3}{8}$ in. in diameter. By using the 183 studs, material and assembly costs were reduced \$40 per unit, or \$4800 per year for a production of 120 units.

Although Table 1 indicates that the capacitor-discharge method is preferred for stud welding of aluminum, arc stud welding was selected in the following

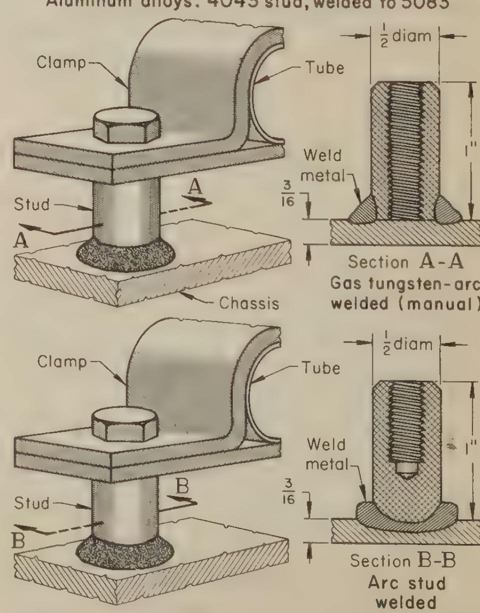


Fig. 6. Aluminum alloy studs attached by arc stud welding, instead of by gas tungsten-arc welding, to an aluminum alloy chassis for an amphibious vehicle (Example 169)

example because of the large weld-base diameter of the stud and because suitable motor-generator equipment was available.

Example 169. Arc Stud Welding of ½ and 7/16-In.-Diam Aluminum Alloy 4043 Studs (Fig. 6)

Tapped aluminum alloy 4043 studs secured clamps for attaching hydraulic, air, oil, and electrical lines to an aluminum alloy 5083 chassis for an amphibious military vehicle. The studs were ½ in. in diameter by 1 or 1½ in. long and tapped with ¼–20 UNC–2B threads, as shown in Fig. 6, or 7/16 in. in diameter by 1 or 1½ in. long and tapped with 10–32 UNF–2B threads.

Originally, the studs were fastened to the chassis by manual gas tungsten-arc welding, but the position and spacing of many of the pads made manual welding difficult and time consuming.

Processing was changed to stud welding, and the arc process was chosen because of the stud weld-base diameter. Also, the 400-amp motor-generator that was used as the power supply for gas tungsten-arc welding provided current with a drooping volt-ampere characteristic and could be used for arc stud welding. Argon shielding gas was used to protect the aluminum alloy base metal and stud.

To prepare for stud welding, the surface of the chassis was cleaned with a stainless steel wire brush just before welding. The studs could not be tapped through because the full base was needed for arc initiation and a full-strength weld.

The plunge adjustment of the gun was critical for good welds. To preload the main plunging spring properly, the stud extended ⅛ to 3/16 in. beyond the gas adapter.

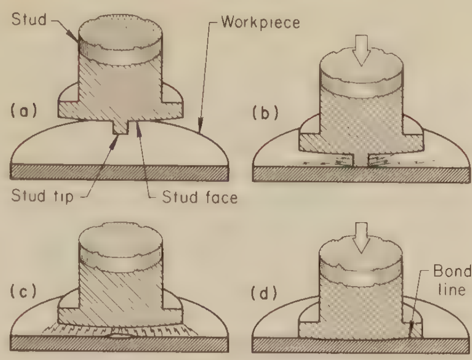
Welding time for the ½-in.-diam stud was 40 ± 2 cycles and the welding current was 640 amp. For the 7/16-in.-diam stud, the welding time was 30 ± 2 cycles and welding current was 570 amp. Reverse polarity was used for both diameters of the studs.

Production time for welding was reduced 60% by the use of stud welding instead of manual gas tungsten-arc welding.

Capacitor-Discharge Stud Welding

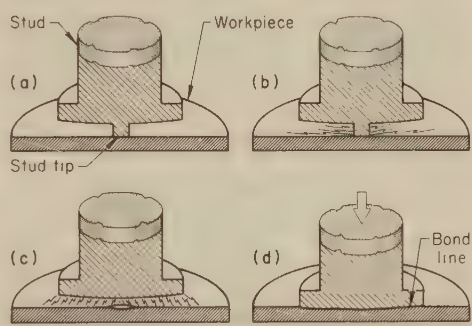
Capacitor-discharge stud welding uses the heat from an arc produced by the rapid discharge of a capacitor. A small tip or projection on the end of the stud is suddenly disintegrated and an arc is initiated. This produces a thin film of molten metal on the end of the stud and on the workpiece adjacent to the stud. The stud is forced into the molten puddle of metal, which extinguishes the arc and completes the weld. Flux is not needed in welding steel; argon shielding sometimes is used in welding aluminum alloys by the drawn-arc method.

There are three methods of capacitor-discharge stud welding: the initial-gap, initial-contact, and drawn-arc methods. The initial-gap and initial-contact methods have a weld time of 3 to 6 milliseconds, which prevents heat buildup and permits welding of fasteners about 5/32 in. in diameter to a steel base metal as thin as 0.030 in. without pronounced distortion, discoloration or burn-through. Weld penetration is slight, which permits many dissimilar metals to be welded with acceptable strength and metallurgical structure. Also, paint, plating or plastic coating on the surface opposite the weld is not damaged. Teflon coating on the inner surface of 0.040-in.-thick aluminum pans is not damaged when studs are welded to the outer surface. Small fastener-component cups made of low-carbon steel, stainless steel, aluminum alloy, or copper alloy have been capacitor-discharge welded to various base metals.



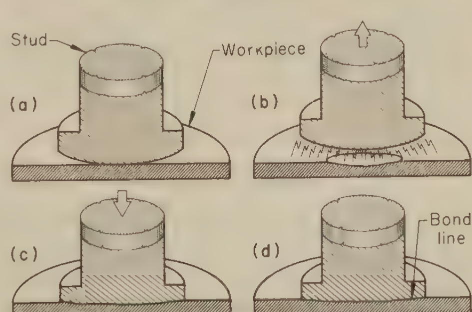
(*a*) The stud is initially positioned above the workpiece. (*b*) When the unit is triggered, the stud holder is released and plunges the stud to the workpiece with the capacitor-discharge voltage impressed on the stud. When the stud tip contacts the workpiece, welding current starts to flow and an arc is formed. (*c*) The tip disintegrates when it contacts the workpiece. Arcing between the stud and the workpiece melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth. (*d*) The stud is plunged into the puddle of molten metal, to complete the weld.

Fig. 7. Sequence of steps in initial-gap capacitor-discharge stud welding



(*a*) The stud is initially in contact with the workpiece. (*b*) When the welding current is turned on, the tip softens and disintegrates, and the arc is initiated. (*c*) Arcing between the stud and the workpiece melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth. (*d*) The stud is plunged into the puddle of molten metal, by spring pressure, to complete the weld.

Fig. 8. Sequence of steps in initial-contact capacitor-discharge stud welding



(*a*) The stud is initially in contact with the workpiece. (*b*) When the current is turned on, the current surges into the stud tip, and the stud is then immediately raised, to draw the arc. The heat of the arc melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth. (*c*) When the welding current is turned off, the solenoid in the gun is de-energized and the stud plunges into the puddle of molten metal. (*d*) Finished weld, with little or no fillet.

Fig. 9. Sequence of steps in drawn-arc capacitor-discharge stud welding

The drawn-arc method has an arc time of 6 to 12 milliseconds; it is the method best suited for base metals that have light rust, mill scale, or surface irregularities.

Straight polarity (stud negative, workpiece positive) is used for capacitor-discharge welding.

Procedures and characteristics of the three types of capacitor-discharge stud welding are described below.

Initial-Gap Welding. In this method, the stud is positioned away from the surface of the workpiece, as shown in Fig. 7. The gun has a solenoid that holds the stud away from the workpiece and a means for moving the stud toward the workpiece rapidly.

When the gun is triggered, the stud holder is released and plunges toward the workpiece with the capacitor-discharge voltage impressed on the stud. As the stud tip contacts the workpiece, welding current starts to flow and an arc is formed that disintegrates the tip. The arc melts metal on the face of the stud and on the workpiece surface opposite the stud. Continued movement of the stud extinguishes the arc and forges the stud into the workpiece. Welding force is usually 5 to 7 lb.

The high-intensity arc has a duration of 3 to 6 milliseconds, and the melted surface layer on each part is only a few thousandths of an inch thick. Because of the brief energy span, the reverse side of the workpiece is almost never marked. There is very little weld spatter at the base of the stud, and a clean weld is produced.

Initial-Contact Welding. In this method, the stud is initially placed in contact with the workpiece as shown in Fig. 8. The gun does not contain a solenoid, but has a means for moving the stud toward the workpiece rapidly. When the gun is triggered, the welding current disintegrates the tip on the stud and an arc is initiated. This causes metal to be melted on the face of the stud and in the area on the workpiece opposite the stud. A welding force of 5 to 7 lb plunges the stud into the molten puddle of metal, which extinguishes the arc and completes the weld.

As in the initial-gap method, the high-intensity arc has a duration of 3 to 6 milliseconds, and the melted surface layer on each part is only a few thousandths of an inch thick. The weld is completed with little reverse-side marking.

Drawn-Arc Welding. In this method, the stud is initially in contact with the workpiece and is then withdrawn to initiate the arc, as shown in Fig. 9. The gun is fitted with a solenoid to withdraw the stud and has a means for moving the stud toward the workpiece rapidly. Welding force is usually 10 to 12 lb.

The high-intensity arc has a duration of 6 to 12 milliseconds; therefore, the layer of molten metal on the stud and workpiece is slightly thicker than for the other capacitor-discharge methods. Also, the work surface can be more rough, pitted and scale coated than for the other two methods.

The power supply is an electrostatic storage system in which the weld energy is stored at low voltage in capacitors having a high capacitance. Because energy is stored, power requirements are low. For portable or hand-held guns, the capacitors are charged by a 115-volt, alternating-current, single-phase power supply. Production models or bench models operate on 230 to 460-volt, alternating-current, single-phase or three-phase power. The output rating of the capacitors ranges from 40,000 to 200,000 microfarads.

Solid-state control units supply signals for several purposes: to energize the solenoid in the welding gun for the initial-gap and drawn-arc methods; to initiate the pilot arc; to de-energize

the solenoid when applicable; and to discharge the required welding current from a bank of capacitors. Precise timing of functions makes possible the exact timing sequence required for maximum performance under a given set of conditions, or for a wide range of conditions. Because of the short, precise timing needed, electromechanical or electrical controls are unsatisfactory for capacitor-discharge stud welding.

Studs can have a shank of any shape, but the weld base must be round. Most studs have a flanged or enlarged base. (A larger weld base provides a stronger weld.) The weld-base diameter of the stud generally ranges from 1/16 to 5/16 in. The maximum diameter is usually 3/8 in.

For the initial-gap and the initial-contact methods, the weld end is provided with a tip that is carefully designed for each application. The tip is small and cylindrical or conical. These tips are used to initiate the arc. Studs for the drawn-arc method have a pointed or convex shape on the end to be welded. This shape helps to initiate the arc at the center of the stud and prevents arcing at the periphery of the stud when it is held one or two degrees from perpendicular with the workpiece. Studs for the drawn-arc method are similar to round-weld-base studs used for arc stud welding, but they have a larger nose radius (flatter tip), because no flux is used and there is less melting at the end of the stud.

In addition to the tip, only a small amount of metal is melted from the stud, which means that the welded length is almost the same as the unwelded length. Standard studs have a minimum length of 3/8 in., but studs for automotive trim are 5/32 in. long.

Standardization of stud size is desirable for efficiency in production-line operations on related or similar items. In Example 172, aluminum studs were standardized so that they could be used for attaching handles to more than one type of utensil.

Stud Location. The method of locating studs depends on several factors, such as the accuracy requirements, whether the welding gun is fixed or portable, the production rate, and the size and shape of the workpiece.

Accuracy of location when the welding gun is portable depends on the care in laying out the workpiece. The use of templates with bushings can result in locational tolerances of ±0.020 in. or less. Because the tips on the weld end of the studs used for the initial-contact and initial-gap methods are carefully designed to maintain the required arc, centerpunch marks cannot be used; very lightly scribed lines are suggested when use of templates is uneconomical.

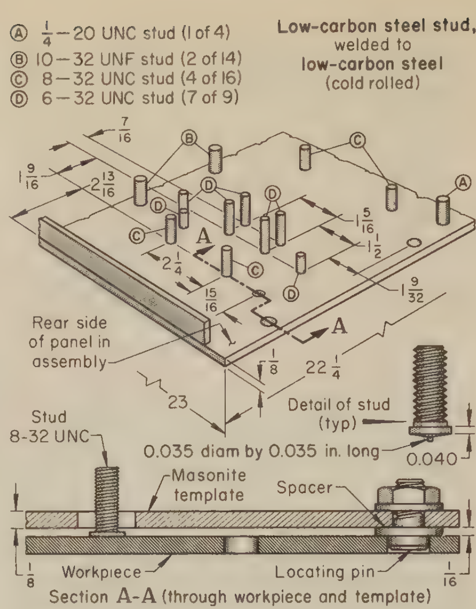


Fig. 10. Mounting base on which studs for electrical components were capacitor-discharge stud welded, and the locating template used (Example 170)

In the following example, a masonite template located the studs to a tolerance of ±1/32 in.

Example 170. Capacitor-Discharge Stud Welding of Mounting Studs to an Electrical Panel (Fig. 10)

The mounting base for the power-supply components of a small telephone system was a 22¼-by-23-by-⅛-in. panel of cold rolled low-carbon steel (Fig. 10). Originally, holes were drilled in the panel, and then machine screws were inserted and held by an assembler from the front of the panel while a second man positioned the components and secured them with nuts from the rear.

Processing was changed to initial-contact capacitor-discharge stud welding, and 43 low-carbon steel studs were welded to the panel. Components were then placed over the studs and secured with nuts from the rear of the panel by one assembler.

The studs, which had a flanged weld base, were 3/8, 1/2 and 5/8 in. long and had full-length threads. Nine studs had 6–32 UNC threads; sixteen had 8–32 UNC threads; fourteen had 10–32 UNF threads; and four had ¼–20 UNC threads.

For welding, the panel, with the ground cable attached, was placed flat on a workbench. A masonite template with locating holes spaced as needed located the studs to a tolerance of ±1/32 in. (Fig. 10). The holes were color coded according to the stud length and diameter, and fit the nose of the welding gun. Spacers 1/16 in. thick between the template and panel prevented template damage from arcing and also permitted the gases developed during welding to escape.

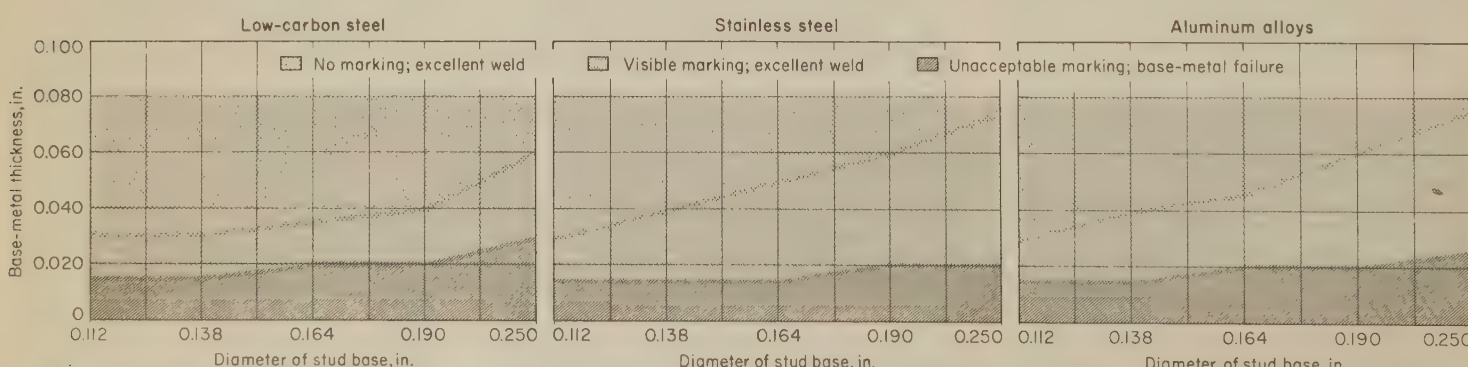
The 10-amp power supply had a nominal available capacitance of 65,000 microfarads, and was charged by 115-volt, single-phase alternating current. The capacitor-discharge output voltage was changed for each stud diameter; otherwise, excessive spatter occurred when the smaller studs were welded with the same voltage used for the ¼-in.-diam studs.

Total welding time was about 3 sec per stud; production was 15 panels per hour.

Production units equipped with various types of workholding and locating tooling can provide tolerances of ±0.008 in. or less. Precise location requires high-quality welding equipment, tooling and fasteners.

Base-metal thickness vs stud size is of interest when the appearance of the product is a prime consideration. Reverse-side marking is the principal effect involved in appearance. In some applications, especially where the largest possible stud diameter is desired for a given base-metal thickness, slight-to-heavy reverse-side marking is acceptable. Figure 11 shows the degree of reverse-side marking that occurs on the base metal for different stud-base diameters when welding similar combinations of low-carbon steel, stainless steel, and aluminum alloys. The data shown in Fig. 11 were compiled by welding both flanged and nonflanged studs to the base metal in a bench-type automatic or semiautomatic stud welder, using the initial-gap capacitor-discharge method.

Honeycomb panels in which face sheets are brazed to the core occasionally have small unbonded areas that can be repaired by passing a stud through the cover sheet and core and then capacitor-discharge stud welding one end to the inner surface of the lower sheet, as described in the following example. The other end of the stud is then gas tungsten-arc welded to the outer surface of the top sheet. This type of repair can be used when the underside of the panel is not accessible,



Degree of reverse-side marking that occurs on the base metal for different stud diameters when welding similar combinations of low-carbon steel, stainless steel, and aluminum alloy. The areas are separated by bands rather than sharp lines, because the point at which a combination will produce reverse-side marking or base-metal failure is difficult to determine with precision.

Fig. 11. Effect of stud diameter and base-metal thickness on reverse-side marking in initial-gap capacitor-discharge stud welding

or when a through hole and weld on the underside can cause a leak — for instance, when the face sheet forms part of a fuel-tank enclosure. When feasible, plain pins are used that extend through the honeycomb panel and are gas tungsten-arc welded to the exposed faces of the panel.

Example 171. Repair of Stainless Steel Honeycomb Panels by Capacitor-Discharge Welding (Fig. 12)

The unbonded area in the honeycomb panel shown in Fig. 12 was repaired by stud welding one end of a ⅛-in.-diam type 321 stainless steel stud to the inner surface of the 0.040-in.-thick PH 15-7 Mo stainless steel bottom sheet. The other end of the stud was subsequently gas tungsten-arc welded to the top sheet.

A portable capacitor-discharge welding gun, with the controls set for the initial-gap method, was used. Both cables were uncoiled and extended so that welding current would be consistent. Straight-polarity direct current was used.

Extreme care was taken in preparing the panel for stud welding. The location of the stud on the top sheet was marked by a small centerpunch indentation, and then a small pilot drill was used to make a hole through the top sheet and the core. Next, the hole was enlarged to 5⁄32 in. in diameter, to within 1⁄16 in. of the bottom sheet. Drill stops prevented drilling too deep, which would have damaged the inner face of the bottom sheet. A flat-bottom drill and a flat end-mill were then used to remove the remaining core and any brazing alloy on the bottom sheet. Drill chips and pieces of the core and brazing alloy were removed with an electromagnet and a vacuum nozzle small enough to enter the hole. The depth of the hole was measured with a depth micrometer, so that the stud welding gun could be set for the proper initial gap of 0.085 in.

After the hole had been properly prepared, a plastic insulator, which insulated the top sheet and core from the stud, was placed in the hole (Fig. 12). The stud, which was held by the stud holder in the gun, was then positioned in the insulator. The gun was held so that the stud was perpendicular to the surface to which it was to be welded.

After stud welding, a gas tungsten arc was used to cut off the portion of the stud extending beyond the top sheet. Cutting the stud to length with a saw would have damaged the stud weld unless special precautions were taken.

The top of the stud was then gas tungsten-arc welded to the top sheet, and the bead was ground flush, if this was required by the application.

Several sample welds were made and tested to determine whether the proper machine settings had been selected. The sample stud weld and the production weld were tested by applying a torque wrench to a special stud-gripping tool. A minimum torque of 10 in.-lb was specified.

The minimum honeycomb facing-sheet thicknesses and torque values for studs of various diameters are:

Stud-base diameter, in.	Minimum sheet thickness, in.	Minimum torque, in.-lb
1⁄16	0.008	1
3⁄32	0.012	4
⅛	0.018	10
3⁄16	0.025	30
¼	0.035	75

A backing block of copper must be used to minimize burn-through and prevent distortion if sheet thickness is less than 0.030 in.

Cooking Utensils. Studs are welded to cooking utensils and lids made of copper, stainless steel, and natural-finish or coated aluminum alloys for attaching handles and legs. The studs can be round, hexagonal, square, rectangular, or trapezoidal, and stud length can vary from as short as can be held in a stud holder to 2 in. Studs are drilled and tapped, drilled for self-tapping screws, slotted, or supplied with threaded extensions.

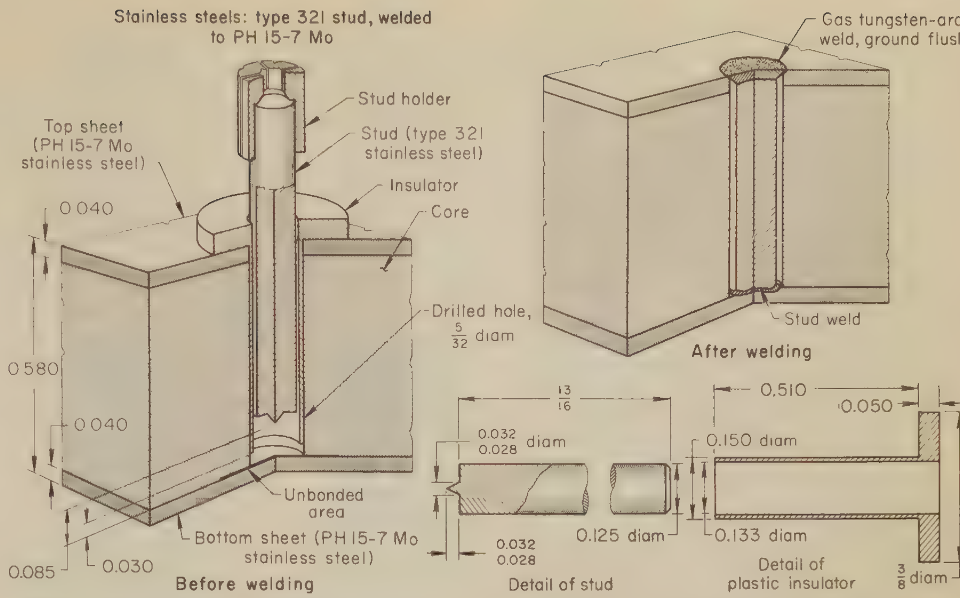


Fig. 12. Stainless steel honeycomb panel that was repaired by capacitor-discharge stud welding and subsequent gas tungsten-arc welding to close the hole (Example 171)

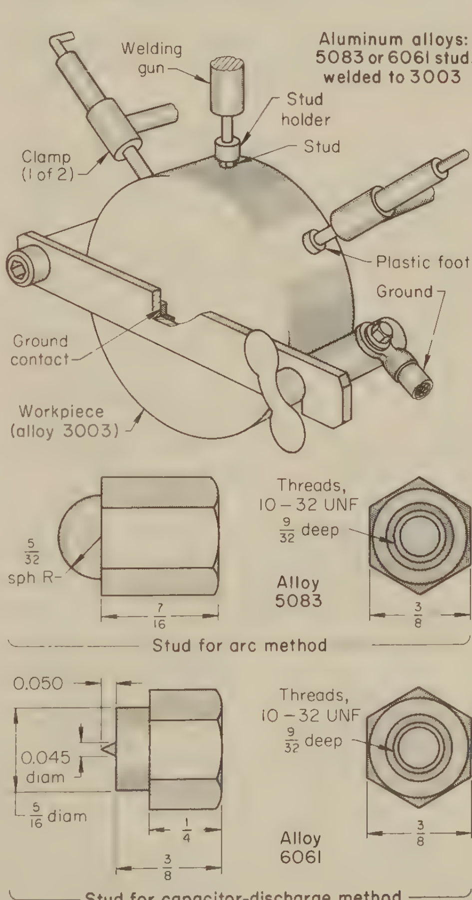


Fig. 13. Tooling arrangement for welding a female stud made of aluminum alloy to an aluminum alloy cooking utensil. Capacitor-discharge stud welding replaced arc stud welding, which had replaced brazing. (Example 172)

Formerly, handles were attached to utensils by riveting, brazing, or resistance spot welding. Knobs were attached to lids by spot welding or by machine screws through a hole in the lid. The introduction of Teflon-lined pans and colored enameled pans made riveting and spot welding undesirable, and stud welding was used. A comparison of arc and capacitor-discharge stud welding for attaching aluminum alloy studs to Teflon-coated and natural-finish aluminum alloys is given in Table 2.

In the example that follows, aluminum studs were arc stud welded to cooking utensils made of aluminum without discoloring the inner surface or distorting the sidewalls. However, when the wall thickness was reduced and a Teflon coating was added to the inner surface of the utensil, the studs were capacitor-discharge stud welded, because weld penetration was less than with arc stud welding.

Example 172. Attaching Studs to Aluminum Cooking Utensils by Arc and Capacitor-Discharge Stud Welding (Fig. 13)

When aluminum alloy 5083 studs were arc stud welded to the body of ⅛-in.-thick alloy 3003 utensils, a setup similar to that shown in Fig. 13 was used. The workpieces were cleaned by vapor degreasing before stud welding.

The arc stud welding machine had a power rating of 85 kva. The secondary welding current was 220 amp. Argon shielding gas and ceramic ferrules were used to control weld quality. Burn-off of the studs was about 3⁄32 in. Air-operated clamps were used on each side of the gun, for fixturing, as shown in Fig. 13. The surfaces of the clamps contacting the workpiece were made of plastic or some other nonconductor of electricity, to prevent arcing at the contact points. The ground connection was made by a shoe on the bottom of the pan where pits produced by arcing would be less noticeable or objectionable.

Welding time was 12 cycles, and one operator could weld 300 studs (300 utensils) per hour using a column-mounted gun and a cast epoxy locating fixture. The relative position of the gun and fixture was adjustable, to ensure correct location of the stud on the pan body. Maintaining a production rate of 300 utensils per hour in

brazing (the operation previously used) had required three brazers, one man for removing flux, three buffers, and one part-time worker who resized the utensils that were distorted by the brazing operation.

The process was changed to initial-gap capacitor-discharge stud welding when the thickness of the pan was reduced and a Teflon coating was applied to the inner surface. Weld penetration was less than for arc stud welding, and thus the Teflon coating was not damaged; also, the heat-affected zone was smaller. Studs of aluminum alloy 6061 were used, and were standardized so that they could be used on several types of utensils.

The input power to the capacitors was 440-volt, 20-amp, three-phase, 60-cycle alternating current. The capacitors had a maximum rating of 200,000 microfarads. Welding time was 4 milliseconds, and the production rate was 900 pans per hour. The gap between the stud and pan was not critical and was set at 1½ in. for ease of loading and unloading the fixture. The fixture used for capacitor-discharge stud welding was similar to that used for arc stud welding.

The handle assembly, which consisted of an aluminum ferrule, a plastic handle, and a threaded bolt, was accurately tightened by an air-operated torque wrench.

At the beginning of each shift, or when restarting the machine after a long shutdown, sample welds were made and torque tested to destruction. During production, studs were nondestructively tested at a predetermined torque at random intervals.

Both stud welding methods provided a joint as strong as those made by riveting, brazing, and spot welding.

Metals Welded

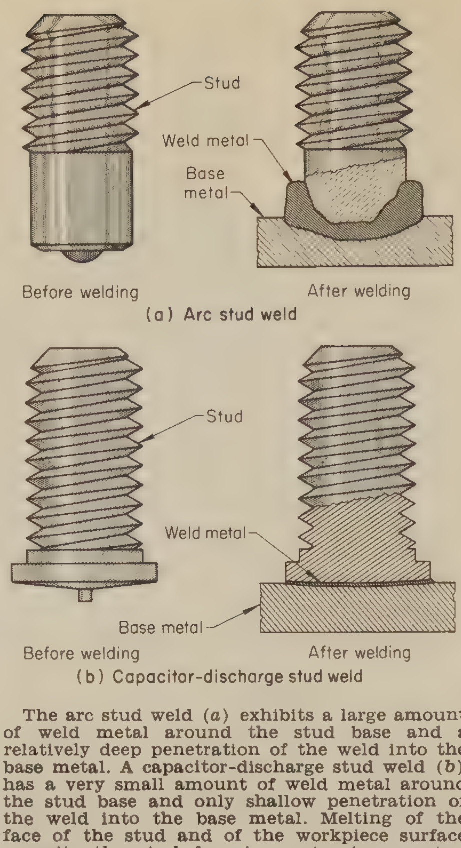
All metals that are readily welded by other arc welding processes are suitable as base metals for stud welding, with proper selection of stud metal. The electrical resistivity and melting temperature of the parts to be joined have little effect on the weld, if both parts are electrical conductors. Table 4 lists typical combinations of base metal and stud metal that have been welded.

Stud welding of various base metals is discussed in the following sections.

Carbon steel workpieces with a carbon content of 0.30% or less usually can be stud welded without preheating. Provided the diameter of the stud is in proper relation to the thickness of the base metal, steel with more than 0.30% C, in thicknesses of less than ⅛ in., can be stud welded without preheating, because of the lower quenching effect of the base metal.

Stud welding of the medium-carbon steels (1030 to 1050) generally is successful, provided the correct preheating and postheating procedures are followed, as discussed next for high-carbon steels.

High-Carbon Steel. In stud welding steel with 0.45% C or more, martensite, a hard, brittle constituent, forms in the steel base metal under the stud. In effect, the base metal has been spot hardened, and the hardening is usually accompanied by cracking. In welding plain carbon steel of high carbon content, preheating of the base metal is suggested because it prevents formation of cracks. Postheating is less effective because cracks have already formed, but it will prevent the propagation of cracks. Depending on the carbon content of the steel base metal, a typical preheating temperature is 700 F and a typical postheating temperature is 1200 F. The hardenable alloy steels are either preheated or postheated, or both, depending on the product requirements.



The arc stud weld (*a*) exhibits a large amount of weld metal around the stud base and a relatively deep penetration of the weld into the base metal. A capacitor-discharge stud weld (*b*) has a very small amount of weld metal around the stud base and only shallow penetration of the weld into the base metal. Melting of the face of the stud and of the workpiece surface opposite the stud face is greater in arc stud welding than in capacitor-discharge stud welding.

Fig. 14. Sections through low-carbon steel studs that were arc and capacitor-discharge stud welded to low-carbon steel base metals

When considering stud welding of high-carbon steel, sample pieces should be welded experimentally, to determine whether the operation is feasible.

Table 4. Typical Combinations of Base Metal and Stud Metal for Stud Welding

Base metal	Stud metal
Arc Stud Welding	
Low-carbon steel, 1006 to 1025	Low-carbon steel(a); stainless steel, series 300(b)
Stainless steel, series 300(b), 405, 410 and 430	Low-carbon steel(a); stainless steel, series 300(b)
Aluminum alloys, 5000 series	Aluminum alloy 5086
Capacitor-Discharge Stud Welding	
Low-carbon steel, 1006 to 1025	Low-carbon steel(a); stainless steel, series 300(b); copper alloys 260 and 268
Stainless steel, series 300(b) and 400	Low-carbon steel(a); stainless steel, series 300(b); copper alloys 260 and 268
Aluminum alloys, 1100, 3000 series, 5000 series, 6061 and 6063	Aluminum alloys 1100 and 5086
ETP copper, lead-free brass and rolled copper	Low-carbon steel(a); stainless steel, series 300(b); copper alloys 260 and 268
Zinc alloys (die cast)	Aluminum alloys 1100 and 5086

(a) 0.23% C max, 0.60% Mn max, 0.04% P max and 0.05% S max. (b) Except for the free-machining type 303 stainless steel.

Low-alloy high-strength steels and most structural steels with a carbon content of more than 0.15% may require moderate preheating, to obtain required toughness in the weld area. An oxy-fuel gas heating torch can be used, because only a localized preheated zone is needed.

Some heat treatable structural steels are sufficiently hardenable in the heat-affected zone to be sensitive to underbead cracking. For maximum toughness, preheating at 600 to 700 F is necessary.

Galvanized Steel. In the construction of buildings and bridges, arc stud welding can be used to weld low-carbon steel shear connectors and concrete anchors directly to steel beams by burning through the galvanized metal decking, without prepunching it. Steel decking up to 0.064 in. thick that is black or bare, or has been electrogalvanized, or has been hot dip galvanized and wiped and has a coating of 0.50 oz of zinc per square foot can be burned through with ½, ⅝ or ¾-in.-diam studs, provided enough welding current is used. Hot dip galvanized sheet 0.040 in. thick coated with 1¼ oz of zinc per square foot also can be burned through. Steel decking 0.060 in. thick coated with a weldable grade of paint (two coats on the bottom side only or one coat on each side) can be burned through using ½-in.-diam studs. Painted sheets that are 0.048 in. thick can be burned through with ⅝ and ¾-in.-diam studs. Specially designed ferrules are used for all coated metals.

The areas on the steel beams to which the studs are to be welded should be cleaned of scale, rust or dirt by wire brushing or grinding, and the steel decking should be free of dirt, water, snow and ice.

Ductwork and other products of galvanized steel can have low-carbon steel studs welded to them. Such studs are used to support insulation, wiring and piping; the welds have adequate strength for this purpose.

Stainless Steel. The austenitic stainless steels 302, 304, 305, 309, 310, 316, 321 and 347 can be arc and capacitor-discharge stud welded. Martensitic stainless steels are subject to air hardening and usually are brittle in the weld area and heat-affected zone unless annealed after welding.

The power requirements for welding stainless steel studs are about 10% greater than those required for welding carbon steel studs.

Stainless steel studs can be welded to stainless steel and to low-carbon steel base metals. Because of dilution of chromium from a stainless steel stud by a low-carbon steel base metal, the resulting weld metal may have a high hardness, especially if the carbon content of the base metal is more than 0.20%. Such difficulties can be minimized by using fully annealed studs with a higher chromium-nickel content. Free-machining stainless steel studs are not readily stud welded.

Aluminum alloys can be welded by both the arc and capacitor-discharge methods, but more are welded by the capacitor-discharge method.

Aluminum alloys of the 1100, 3000 and 5000 series generally are excellent for stud welding; alloys of the 4000 and 6000 series are acceptable; alloys of the 2000 series are poor.

The power supply, welding gun, and controls are the same as those used for steel. Argon or helium shielding gas is required. Reverse-polarity direct current (stud positive, workpiece negative) is used.

Studs are made of aluminum-magnesium alloys, including 5086, 5356 and 6061, and of alloy 1100. The aluminum-magnesium alloys have high strength and good ductility and are metallurgically compatible with most of the other aluminum alloys.

A longer arc is needed for welding aluminum alloy studs than for welding steel studs. A cylindrical or conical projection on the end of the stud helps to initiate the arc and to establish the longer arc.

Longer weld times and lower welding currents are used for welding aluminum alloys than for welding low-carbon steel, as shown in Table 3.

Magnesium alloys have been arc stud welded in a test program. High-strength welds were made with a gas shield and reverse-polarity direct current. Ferrules were not used. Helium shielding gas was preferred over argon, because it provided a wider range of welding times and higher-strength welds. (For data, refer to: L. F. Lockwood, Gas-Shielded Stud Welding of Magnesium, *Welding Journal*, April 1967.)

Zinc alloy die-cast parts can have fasteners stud welded to them instead of cast integrally. The fasteners can be welded to the parts without destroying the decorative coatings that have been previously applied. In the automotive industry, stud welding has been used for attaching fasteners to emblems, dashboards and taillight brackets that were zinc alloy die cast.

Studs of aluminum alloy 1100-H18 are most successful, but studs of aluminum alloy 5086, copper alloys, low-carbon steel, and stainless steel have been used for limited applications, or where greater stud strength was needed. In one application, a ¼-in.-diam aluminum alloy stud was stud welded to a zinc die-cast part with a capacitor-discharge machine set for 150 volts and 100,000 microfarads. Peak amperage was 7000. Weld time was 5 milliseconds. (Source: E. J. Fay, Welding Fasteners to Zinc Die Castings, paper presented at Third National Die Casting Exposition and Congress, Detroit, Nov 17-20, 1964)

Inspection and Quality Control

Stud welds are inspected visually or mechanically.

Visual inspection depends on an inspector's interpretation of the fillet around the stud base. An arc stud weld has a pronounced fillet; a capacitor-discharge weld has a very small fillet.

A section through a satisfactory arc stud weld is shown in Fig. 14(a). Much of the molten metal in the weld puddle was forced out from under the stud and retained by the ferrule, but some metal remained at the base of the stud. Heat-affected zones occur in both the stud and the base metal.

A section through a capacitor-discharge weld (Fig. 14b) shows a very small fillet. The heat-affected zones on the stud and in the base metal are very shallow, but the weld is sound.

A satisfactory fillet on an arc stud weld and some typical defective welds are shown in Fig. 15. A well-formed fillet is shown in Fig. 15(a). Figure 15(b) shows an incomplete weld that resulted because a malfunction in the gun prevented plunging of the stud at the end of arcing. If the gun is not held perpendicular to the surface of the workpiece, a partial fillet can result, because of cocking of the ferrule, which allows weld metal to escape, as shown in Fig. 15(c). A plunge that is too short will result in a partial fillet because not enough metal is extruded from the weld puddle, as shown in Fig. 15(d). A partial weld can also result when foreign material is present that impedes melting during arcing. The results when temperature is too low and too high are shown, respectively, in Fig. 15(e) and (f). The electrical connections, power setting, time cycle and arc length should be checked when a cold weld occurs. The power setting or the time cycle, or both, should be decreased when temperature is too high.

In a good weld formed by the capacitor-discharge method, the stud is perpendicular to the workpiece, with very little weld spatter around the base and a weld fillet that is very thin and even (see Fig. 14b). Incomplete welds can result from a malfunction of the gun or from an inadequate plunge, as in arc stud welding. If the welding tool is not held perpendicular to the workpiece, the stud will be tilted and a partial weld will be produced at the edge of the stud contacting the workpiece.

A cold weld is produced when the base of the stud is not melted to the edge and only a small area in the center of the stud is fused. This can be corrected by increasing the power-discharge setting. Excessive weld spatter and weld metal encasing the base is called a hot weld; it is usually caused by a power-discharge setting that is too high. A hot weld usually burns through thin sheet.

Mechanical testing of studs usually is done before starting a production run, to determine whether satisfactory welding schedules have been developed, and before each shift and during a production run, to ensure that welding conditions have not changed.

Stud welds are tested by applying torque until a predetermined torque load is reached or until failure occurs. The torque load applied and the number of studs tested depend on the application requirements.

Stud welds are also tested by bending. The stud is struck with a hammer or bent with a short length of tube placed over it. If the weld is good, any failure will occur in the shank of the stud or in the base metal. Some applications specify that the stud be bent 45° to 90° from its axis without failure; for other applications, a bend of 10° to 15° is adequate.

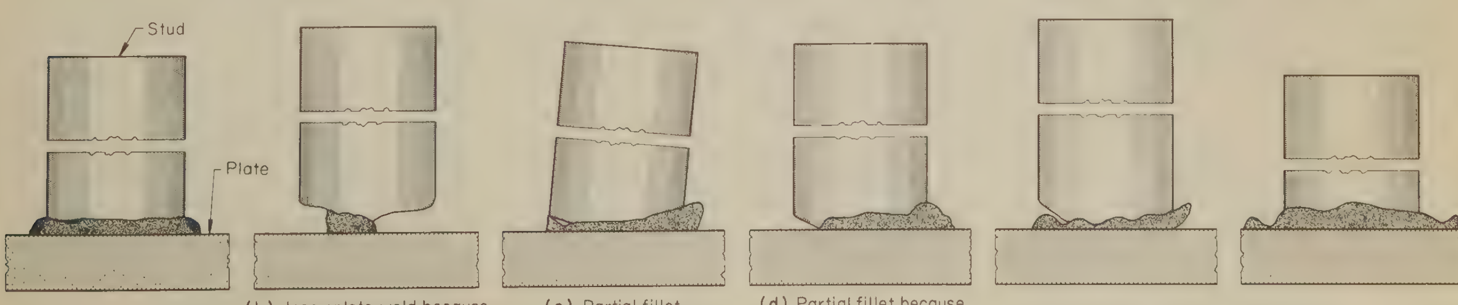
Aluminum and brass studs should not be bent with a hammer; a tube-type bending tool should be used.

Because bend tests can damage the studs so that they are usable only in very low-stress applications, bending should be done on samples, not on production parts. However, there are some applications in which the stud can be bent and used as is, or can be bent, straightened and then used — provided that no failure of the stud, the base metal or the weld occurred during the bend test or during straightening.

Stud Welding vs Alternative Processes

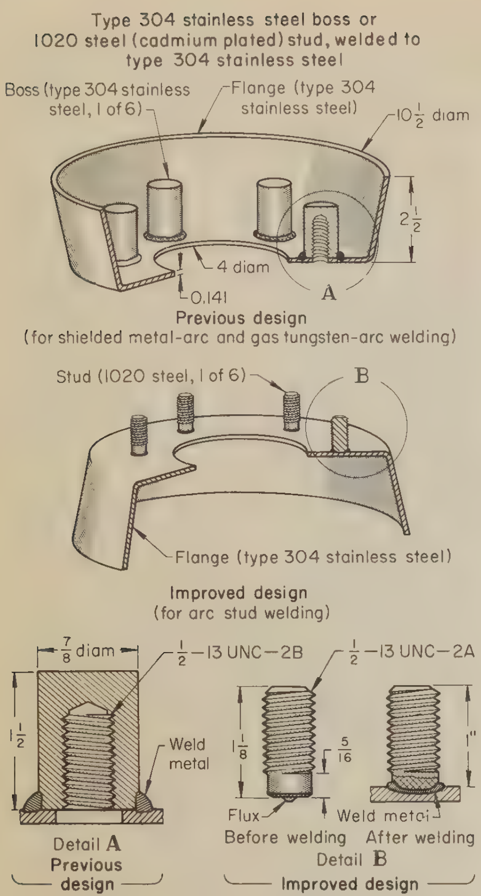
Stud welding is frequently selected over other processes because of good appearance of the workpiece, accessibility of the workpiece surface, requirements for airtight and watertight joints, and the need for complete fusion to minimize electrical resistance and to obtain good heat transfer.

Arc stud welding replaced gas tungsten-arc welding in Example 169. In Example 170, capacitor-discharge welded studs were used instead of screws and nuts. Arc stud welding replaced brazing in Example 172, but was replaced by capacitor-discharge stud welding when the base metal was changed.



(a) Well-formed fillet (b) Incomplete weld because of malfunction in gun (c) Partial fillet because of tilted gun (d) Partial fillet because plunge too short (e) Cold weld (f) Hot weld

Fig. 15. Well-formed fillet on an arc stud weld (left) and typical fillet defects. Capacitor-discharge welded studs have similar characteristics (see text for discussion).



Item	Gas tungsten-arc welding	Arc stud welding
Cost per Piece		
Fabrication:		
Setup	$0.035	$0.016
Operating	1.592	0.041
Assembly:		
Setup	0.032	0.004
Operating(a)	0.787	0.167
Material	4.188(b)	0.675(c)
Total cost per piece	$6.634	$0.903
Total savings per piece		$5.731

(a) Includes welding and testing for air leaks or strength of weld. (b) Includes cost of six screws, six bosses, and welding supplies. (c) Includes cost of six studs and nuts.

Fig. 16. Stainless steel valve-outlet flange for which weld quality was improved by changing from shielded metal-arc to gas tungsten-arc welding, then to arc stud welding. Costs were greatly reduced when flange was redesigned for arc stud welding. (Example 173)

In manual arc welding, slag inclusions and start-and-stop overlaps affect weld quality and can cause porosity. For airtight joints, porosity cannot be tolerated. In the next example, stud welding improved weld quality, provided a strong joint, and reduced cost by more than 85%.

Example 173. Cost Comparison for Gas Tungsten-Arc Welding vs Stud Welding of Fasteners to Valve Outlet Flanges (Fig. 16)

The type 304 stainless steel drain-valve outlet flange shown as the Previous design in Fig. 16 was made by welding six tapped bosses ⅞ in. in diameter by 1½ in. long to the flange. Originally, welding was done by the shielded metal-arc process, using ⅛-in.-diam E308-16 stainless steel electrodes.

The flanges were placed in a combination welding-and-leak-test fixture, and the bosses were welded to the inner surface of the flange, as shown in Fig. 16 (Previous design). Dowel pins with small holes for the passage of compressed air for testing purposes were used to locate the flange and the bosses on a 6¼-in.-diam bolt circle. The pins extended through the flange and into the tapped holes in the bosses. Before the workpiece was removed from the fixture, the welds were air tested for leaks with the aid of a soap solution.

Welds made by the shielded metal-arc process were not of uniform quality and slag entrapment and start-and-stop overlaps occurred. Weld quality was improved by changing to manual gas tungsten-arc welding, but greater operator skill was needed and welding costs were higher.

Arc stud welding was then recommended. Because of engineering requirements, the following changes and tests were made before stud welding was adopted:

1. A fillet about ⅝ in. in diameter that formed around the base of the stud in arc stud welding interfered with leakproof sealing of the valve to the outlet flange, even though a 3/32-in.-thick cork gasket was used between the parts. To overcome this drawback, the hole size in the valve flange was changed from 9/16 to ⅝ in. in diameter.
2. The original specification called for studs of type 304 stainless steel. After tests showed that cadmium-plated low-carbon steel studs were as resistant as stainless steel studs to the particular service environment, the use of cadmium-plated cold drawn 1020 steel studs and nuts was approved. This contributed to a lower material cost.
3. Torque and tension tests were made on sample welds to determine that they had adequate strength, because field failures could occur at weld joints not strong enough to withstand the torque needed to tighten the flange to the valve, and a broken stud would be difficult to replace in the field.

Studs with a weld-base diameter of 7/16 in. and with flux attached to the tip were arc stud welded to the outer surface of the flange, as shown in Fig. 16 (Improved design). The flange was clamped to an indexing fixture that was positioned beneath a column-mounted stud welding gun. Because the stock thickness (0.141 in.) was such that burn-through could occur, the fixture also served as a backing and chill.

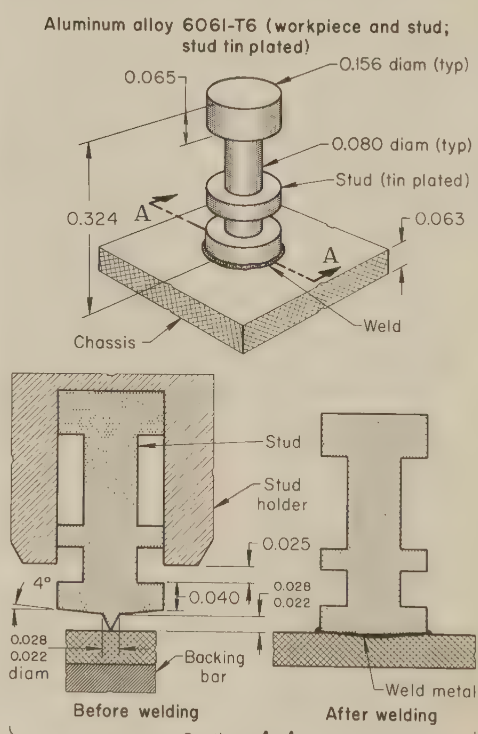


Fig. 17. Tin-plated 6061-T6 stud that was capacitor-discharge stud welded to a 6061-T6 electronic chassis (Example 174)

The power-supply unit had an output rating of 1500 amp. The stud, with flux attached to the tip, extended 3/32 to ⅛ in. below the ferrule when both were inserted in the gun.

Stud welding resulted in improved appearance because only a small heat spot showed on the inner surface of the flange. Also, a leak test was unnecessary because there were no holes in the flange.

Based on a production-lot size of 400 units, the average welding time was 2.87 minutes per piece.

Costs for gas tungsten-arc welding and stud welding are compared in the table accompanying Fig. 16. Savings per unit for stud welding was $5.73, or a yearly total savings of $13,385 for 2336 flanges.

Low-resistance electrical connections and low-cost, reliable joints are required for chassis for electronic equipment. With the aluminum alloys frequently used for the chassis, low-temperature soldering techniques seldom provide the necessary joint reliability. In the following example, tin-plated aluminum connectors were capacitor-discharge stud welded to a chassis, instead of being secured mechanically, to improve joint reliability, and reduce production time and cost.

Example 174. Capacitor-Discharge Welding of Studs to an Aluminum Electronic Chassis (Fig. 17)

Originally, the assembly shown in Fig. 17 was made by mechanically securing the stud to the chassis. Both components were made of aluminum alloy 6061-T6. A better joining method was required when the size of the electronic chassis was reduced, production quantities were increased, and more-reliable electrical connections were needed.

Initial-contact capacitor-discharge stud welding was selected because it provided a strong joint that was free from inclusions and had low electrical resistance. By using tin-plated aluminum studs, a means for making reliable solder connections was provided. Specifications for the chassis stated that the studs were to be perpendicular to the surface within ±1°. Weld spatter was to extend no more than 1/32 in. beyond the diameter of the stud.

The studs were made of alloy 6061-T6 to the dimensions shown in Fig. 17 and were tin plated to a thickness of about 0.002 in. before the welding operation. Cleaning of the studs before welding was not required, but the chassis was acid cleaned to remove surface oxide.

The welding machine, which had an input rating of 110-volt alternating current, had two capacitors, with a total capacitance of 16,000 microfarads. The gun was column mounted, and the chassis was manually positioned for each stud. The machine platen served as a backing, to prevent deflection of the thin sheet and to minimize burn-through.

An air cylinder with an applied air pressure of 60.5 psi held the tip of the stud against the chassis during initiation of the arc, and was used to plunge the stud into the weld puddle after the conical tip disintegrated. The stud holder was made of beryllium copper.

Weld quality was checked during the production run by making four shear samples and testing them to destruction. The minimum acceptable load in shear was 210 lb, but many of the studs withstood a shear load of 340 to 450 lb. Failure in the weld joint was unacceptable. The tin plating on the stud did not affect weld quality unless the plating thickness was excessive.

To determine whether an adequate bond had been made, a 10-lb load was applied to the top of the stud and parallel to the sheet surface. If there was visible movement, the stud was removed and a new one was welded in the same place.

Production rate was 100 welds per hour, with a rejection rate of less than 2%. The cost of each stud was about 3¢.

Percussion Welding

PERCUSSION WELDING is an arc welding process in which the heat is obtained from an arc produced by a rapid discharge of electrical energy, and force is percussively applied during or immediately after the electrical discharge. A shallow layer of metal on the contact surfaces of the workpieces is melted by the heat of the arc produced between them, and one of the workpieces is impacted against the other, extinguishing the arc, expelling molten metal, and completing the weld.

Arc initiation, arc time, and welding force are controlled and synchronized automatically. The power supply usually is a welding transformer or a capacitor (or bank of capacitors). The welding force (forging force) is applied by electromagnetic devices, electromechanical devices, cam-actuated direct drive, springs or gravity.

The heat input is intense, but extremely brief and localized, and enables the percussion welding of one small component to another, of a small component to a larger one, and of dissimilar metals that differ considerably in electrical resistivity and melting temperature. The electrical resistivity of the parts being welded does not noticeably affect the amount of heat generated at the joint. The arc supplies the heat for welding.

The workholding clamp, jaws or chuck of the welding head need not be a good electrical conductor, as in resistance welding, because the amount of current passed is comparatively small and the duration of current flow is extremely brief. The holder material is usually selected primarily for strength and wear resistance; hardened steel is often used.

Relation of Percussion Welding to Stud Welding

Percussion welding and stud welding (described in the preceding article in this volume) are similar in three important respects:

1. Welding heat is obtained from an arc.
2. Force is applied percussively.
3. Arc-starting methods used in the several variations of the two processes are closely similar.

Percussion welding and stud welding differ in various aspects of equipment, technique and process variables. The similarities and differences among the commonly used methods of percussion welding and stud welding are compared in Table 1. Although a clear-cut distinction exists between percussion welding and arc stud welding, there are close similarities among the capacitor-discharge methods of percussion and stud welding.

Percussion welding is principally used for making electrical connections and electrical contact devices; the chief use of stud welding is for joining studs or similar shapes to larger parts for fastening other components.

The examples and most of the text for this article were supplied by members of five Metals Handbook welding committees.

Applicability

Percussion welding can be used to join like and unlike metals that are not usually capable of being flash welded or stud welded.

The process is used for welding fine wire leads to filaments in lamps and to terminals of electrical and electronic components where a reliable joint is needed to withstand shock, vibration and extended service at elevated temperature. It is used in making telephone equipment and other electronic and electrical devices, and for attaching large-area contacts to switch components. Percussion welds can be made a few thousandths of an inch away from glass seals or other heat-sensitive materials without damage to these materials, because the total heat input is small and can be made highly localized.

Percussion welding can be used for butt joints between two wires or between a wire and a rod, and for T-joints between a wire and a workpiece with either a flat or a curved surface. The workpiece can be massive, or it can be thin sheet metal, as in a chassis or a terminal. Stranded wire, as well as solid wire, can be percussion welded in joints of these types. Flat workpieces of any shape can be percussion welded to mating flat surfaces with the aid of an arc-starting nib or projection on one of the members.

Design and Size of Workpieces. The workpieces must be separate; the ends of a continuous workpiece cannot be joined to make a ring. One of the components of the assembly must be designed so that it can be clamped securely in a welding head and be impacted against a stationary component without slippage.

Capacitor-discharge percussion welding (see page 179) can be used to butt weld wires of similar diameters or of greatly different diameters. For some metals, wire diameter can be as small as about 0.005 in.

A wire can be capacitor-discharge percussion welded to a workpiece having a large surface area. In Examples 176 and 177, a 0.020-in.-diam wire was butt welded to a 0.040-in.-diam wire. Welding a 0.032-in.-diam wire to a section of ½-in.-diam tubing that had a wall thickness of 0.062 in. is described in Example 178.

Magnetic-force percussion welding (see page 185) can join flat workpieces with a weld area of 0.04 to 0.70 sq in. in production. An arc-starting nib or projection must be provided on one of the workpieces. Example 180 describes the welding of a contact 0.71 in. square (weld area of 0.50 sq in.).

Workpiece Condition. Heat treated, cold worked or prefinished metals are virtually unaffected by the heat of percussion welding, because the heat-affected zone is very shallow. As discussed in the section on Arc Time and Heat-Affected Zone, on page 178, the heat input is so concentrated at the weld interface and of such short duration that metal more than a few thousandths of an inch away from the weld interface is not affected by the welding heat.

Cleaning is not critical for the production of a sound percussion weld, because at least a thin layer of metal is melted from each workpiece and expelled from the joint.

Metals Welded

Almost any like or unlike metals or alloys can be joined by percussion welding. Work metals of widely dissimilar composition, melting temperature, electrical conductivity, and thermal conductivity can be readily welded together.

Like metals joined include copper alloys, aluminum alloys, nickel alloys, low-carbon steels, medium-carbon steels, and stainless steels. Various combinations of these alloys also have been joined.

Gold, silver, copper-tungsten, silver-tungsten, and silver – cadmium oxide have been percussion welded to copper alloys for commonly used assemblies for electrical contacts.

Copper is routinely percussion welded to molybdenum. Although true welds between these two metals had formerly been considered impossible because of mutual insolubility, electron-beam microprobe analysis has shown copper penetration of 0.0004 in. into molybdenum at the weld interface.

Thermocouple alloys and low-expansion alloys have been percussion welded to molybdenum and other metals. Welds between molybdenum wires, between Cb-1Zr wires, between 85Zr-15Cb wires, and between tantalum wires have been made in air, with a stream of argon gas directed at the joint during welding.

In applications where diffusion during prolonged service at high temperature would produce weak or brittle structures in direct joints between dissimilar metals (for instance, in joints between copper and stainless steel for continuous service at 1200 F), transition joints that include a compatible third metal have been used to prevent this condition.

Percussion welding schedules for joining dissimilar metals are based primarily on the melting temperatures of the metals being joined, although the thermal and electrical conductivities of work metals and the shape and size of workpieces also must be considered. (Table 2 gives conditions for and results of capacitor-discharge percussion welding of several combinations of wire-to-wire and wire-to-stainless plate. Wire size was 0.015 and 0.150 in. in diameter and 0.040 in. square.)

Table 1. Comparison of Process Variables in Percussion and Stud Welding

Item	Percussion welding				Stud welding			
	Capacitor-discharge method			Magnetic-force method	Arc method(a)	Capacitor-discharge method		
	Low-voltage		High-voltage					
Power supply	Capacitor	Capacitor	Capacitor	Transformer(b)	Rectifier(c)	Capacitor	Capacitor	Capacitor
Current supplied to arc	Dc	Dc	Dc	Ac	Dc	Dc	Dc	Dc
Voltage, v	50 to 150	12 to 120	1000 to 3000	10 to 35	60 to 100	100 to 200(d)	100 to 200(d)	100 to 200(d)
Arc-starting method	Nib plus dc voltage (initial gap)	High-frequency ac pulse plus dc voltage(e)	Dc voltage (initial gap)	Nib plus first half-cycle of ac (initial contact)	Nib plus dc voltage (draw arc after contact)	Nib plus dc voltage (initial gap)	Nib plus dc voltage (initial contact, no retraction)	Dc voltage (draw arc by retracting after contact)
Arc time, milliseconds	0.15 to 1	1 max	1 max	8 max	100 to 1000	3 to 6	3 to 6	6 to 12

(a) A ferrule is used to confine the molten metal in this method; flux may be used, depending on workpiece and size. (b) Resistance welding transformer. (c) Arc-welding type of rectifier or motor-generator; no energy storage. (d) Approximate. (e) Initial gap.

Power Supply

Three types of power-supply units, as described below, are used for percussion welding. The first two, low-voltage and high-voltage capacitors, are energy-storage devices that are charged by direct current from a rectifier or motor-generator. The third type — a resistance welding transformer — uses an input of 60-cycle alternating current, and does not involve storage of electrical energy.

Low-voltage capacitors that have high capacitance are used as power supplies in capacitor-discharge percussion welding. The capacitor is charged by direct current from a rectifier or motor-generator, and the welding energy is stored at about 50 to 150 volts (or, occasionally, up to 300 volts) and later discharged to make the weld.

These capacitors are similar to those used to supply power for capacitor-discharge stud welding, but are discharged in about a fourth to a sixth of the time taken by the capacitors used in stud welding. The low voltage makes this type of power supply appropriate for use with hand-held percussion welding guns, for which protection from high voltage would be difficult to provide. Low-voltage capacitors are also used with bench-mounted heads in percussion welding systems that are less expensive than those using high voltage, and that are adaptable to mechanized high-speed production. (See Low-Voltage Capacitor-Discharge Percussion Welding, page 180.)

High-voltage capacitors that have low capacitance are also used to supply power for capacitor-discharge percussion welding. They function the same as low-voltage capacitors, but store the welding energy at 1000 to 3000 volts (or, occasionally, up to 6000 volts).

High-voltage capacitors can produce a more uniform arc discharge, and the use of this type of power supply is one way of avoiding the need for an arc-starting nib. The high voltage allows more latitude in controlling operating variables. However, for hand-held equipment, it is more difficult and costly to provide operator protection against voltages above 1000 volts than against those below 150 to 300 volts. (See "High-Voltage Capacitor-Discharge Percussion Welding", page 184.)

Resistance welding transformers used as power-supply units for magnetic-force percussion welding supply 60-cycle alternating current at low voltage. They are used at a lower impedance and deliver current at a higher voltage (10 to 35 volts) than those used in ordinary resistance welding.

Two transformers are used, as explained in the section on Magnetic-Force Percussion Welding, page 185. The weld is made during the first half-cycle of current flow; thus this system functions essentially like a low-voltage direct-current system without an auxiliary energy-storage device.

Arc Time and Heat-Affected Zone

Arc time is the interval beginning when the arc is initiated and ending when one workpiece strikes the other and the arc is quenched.

Factors affecting arc time include the work metal or combination of work metals, mass of the moving workpiece and moving parts of the machine, nib dimensions, welding voltage and current, welding force, and synchronization of arc initiation with the application of welding force.

The shortest arc time that will permit the formation of a sound metallurgical bond with some penetration into both workpieces is generally used, in order to minimize heating effects on adjacent areas of the workpieces. Typical arc times in percussion welding are up to 1 millisecond for capacitor-discharge welding, and up to 8 milliseconds when using a transformer, as in magnetic-force percussion welding.

Because of the short arc time, the heat-affected zone is very shallow. For capacitor-discharge welding, it is often only about 0.0015 to 0.005 in. In percussion welds between metals that have widely different melting temperatures, the heat-affected zone may be only a few millionths of an inch in the higher-melting metal and 0.015 to 0.025 in. in the lower-melting metal. (See Example 176, on welding of molybdenum to Dumet.)

Because the capacitor-discharge method permits a shorter arc time, this method can be expected to produce somewhat shallower heat-affected zones in a given joint than the magnetic-force method can.

Welding Energy

The charge on the capacitor (or bank of capacitors) and the voltage give an approximate measure of the welding energy expended at the joint in the arc discharge. This energy can be calculated by the following equation:

$$E = \frac{1}{2}Cv^2$$

where E is energy in watt-seconds (joules), C is capacitance in farads, and v is voltage.

The amount of energy used in making a percussion weld depends on the cross-sectional area of the joint, the properties of the work metal or metals, and the depth to which metal is melted on the workpieces.

In welding copper to copper alloy 710 (copper nickel, 20%) in Example 175, welding energy per weld was 2.5 watt-sec, which was equivalent to an energy density of about 8000 watt-sec per square inch of weld cross section. In joining molybdenum to Dumet in Example 176, the welding energy was 5.0 watt-sec per weld, or 16,000 watt-sec per square inch. About 25,000 watt-sec of energy per square inch was needed in joining a platinum-rhodium alloy to copper in Example 177, in which 8 watt-sec was used. In all three of these examples, the weld interface was 0.020 in. in diameter, for a cross-sectional area of 0.000314 sq in.

Welding Current

The welding current pattern (or arc-discharge pattern) in percussion welding varies with the application, and is not usually measured. However, current peaks of 400 and 350 amp, equivalent to more than 1 million amperes per square inch of weld contact area, are reported in Example 175 for capacitor-discharge percussion welding of copper to copper alloy 710 (copper nickel, 20%); and a maximum current density of 855,000 amp per square inch was observed in magnetic-force percussion welding a ⅜-by-5⁄16-in. Ag-CdO contact to a brass terminal, in an operation similar to Example 180.

Figure 2 on page 181 shows a schematic representation of the changes in welding current during capacitor-discharge percussion welding of wires.

A peak current density in the neighborhood of 300,000 amp per square inch is obtained when a low voltage of 80 to 90 volts is used in capacitor-discharge percussion welding of steel to steel, steel to copper, aluminum to aluminum, and brass to aluminum.

Polarity is of no consequence in making percussion butt welds between members made of the same metal and having the same cross section, but can affect results in other types of percussion welds. When the members have different cross sections or different melting points, and the amount of heat input is a critical factor in obtaining a sound weld, the member for which a greater amount of heat input is needed (the member having the larger cross section or higher melting point or thermal conductivity) is ordinarily given a positive polarity.

Table 2. Conditions for and Results of Percussion Welding of Seven Combinations of Work Metals(a)

Workpieces welded	Wire size	Welding voltage, v	Resistance, ohms(b)	Initial gap, in.(c)	Tensile strength, psi	Location of failure
Chromel wire to Alumel wire	0.015-in. diam	130	1.0	⅜	77,300	Alumel
Copper wire to Nichrome wire	0.015-in. diam	160	1.5	⅜	39,100	Copper
Copper wire to stainless plate	0.015-in. diam	150	1.0	1¼	40,000	Copper
Nichrome wire to stainless plate	0.015-in. diam	350	1.0	2¼	145,500	Weld
Chromel-Alumel wire to stainless plate	0.150-in. diam	350	1.0	2¼	65,000	Weld
Thorium wire to thorium wire	0.040 in. square	350	1.0	2¼	Not measured	Wire
Thorium wire to Zircaloy-2 wire	0.040 in. square	350	1.0	2¾	Not measured	Zircaloy-2

SOURCE: W. A. Owczarski and A. J. Palmer, *Metalworking Production*, Aug 9, 1961, p 57-59

(a) The welding machine was similar to that used in Example 178. The capacitor bank had a variable output rated at 20 to 400 microfarads and 600 volts max. The series resistor was a 0 to 7.5-ohm, 50-watt stepless potentiometer. The effective weight of the cantilever was about 6 oz, but additional weight could be added, if needed. (b) Setting of potentiometer. (c) Distance of fall of wire (workpiece) attached to pivoted arm.

The selection of polarity is of special importance in the percussion welding of unlike metals that differ greatly in melting temperature, and is used to minimize the depth of melting, as well as the depth of the heat-affected zone, in the lower-melting metal.

When alternating current is used in magnetic-force percussion welding of work metals for which polarity affects weld quality, sometimes the transformer core must be defluxed during loading time, to ensure the correct polarity. This is done automatically on some machines by passing the second half-cycle at reduced current through the transformer in the direction opposite to that of the first (welding) half-cycle.

Welding Force

The force used in percussion welding is difficult to measure, because it is dynamic rather than static and depends on the velocity and mass of the moving workpiece and moving parts of the machine. Peak loading of 15,000 to 30,000 psi has been observed in dynamic measurements for capacitor-discharge percussion welding.

To produce good welds, the welding force must be adjusted empirically until the desired weld quality is obtained. Welding force can be supplied by an electromagnet, gravity, a cam-actuated direct drive, or a spring, depending on the percussion welding method and the size, shape and arrangement of the parts being welded. It must be great enough to accelerate one of the parts being welded and the moving parts of the machine to a high velocity within the short gap characteristic of percussion welding.

An impact velocity of 80 to 150 in. per second has been used with spring drive in low-voltage percussion welding of wires up to about 0.010 in. in diameter. Velocity was 90 to 100 in. per second in Example 175. A range of 10 to 60 in. per second has been used in joining wires only a few mils in diameter. The application of the percussive force and the welding current must be precisely coordinated.

Because a force-applying component may rebound and put a tensile load on the weld metal while it is solidifying, a means of damping the rebound must be provided. Damping is particularly critical in the welding of small parts.

Arc Starting

Three methods of starting the arc are used in percussion welding.

In one method, the arc is started by applying to the parts being welded a direct-current voltage high enough to overcome the resistance of the air in the gap between the parts as one moves toward the other. The air is ionized, and the flow of welding current is started. This method is used in high-voltage capacitor-discharge percussion welding.

Another method involves superimposing an auxiliary high-frequency, high-voltage alternating current on a low-voltage direct current across the gap between the workpieces. The high-frequency alternating current ionizes the air in the gap, and the low-voltage direct current maintains the arc. This method is used in some low-voltage capacitor-discharge percussion welding; it eliminates the need for preparing a nib on one of the workpieces.

In a third method, a starter nib is prepared on one of the workpieces by cutting it at an angle, or in the shape of a chisel tip or other projection, or by attaching or forming a projection on it. Either a low-voltage direct current (in some low-voltage capacitor-discharge percussion welding) or the first half-cycle of low-voltage alternating current from a transformer (in magnetic-force percussion welding) will create enough heat to melt the nib. It is heated so rapidly when the arc forms that it explodes and molten particles are expelled from between the work surfaces at high velocity. These particles help to form the electric arc, which then spreads progressively over the workpiece surfaces at the interface of the joint being welded.

Capacitor-Discharge Percussion Welding

In capacitor-discharge percussion welding, a direct current with a low voltage of about 50 to 150 volts (or, occasionally, up to 300 volts) or a direct current with a high voltage of 1000 to 3000 volts (or, occasionally, up to 6000 volts) is supplied by a capacitor or bank of capacitors. (See the section on Power Supply, on page 178.)

In low-voltage welding, arc starting is accomplished with the aid of a nib (see "Nib-Starter Machines", page 180) or a high-frequency pulse of alternating current (see "High-Frequency-Start Machines", page 181). In high-voltage welding, no auxiliary arc starter is needed.

The mechanism of arc starting at voltages below the ionization potential of air (about 450 volts) is not clearly understood, but is believed to involve a cold cathode discharge. Arc starting is less consistent below 450 volts than at higher voltages, particularly in welding workpieces of large diameter.

Because arc equilibrium conditions are not achieved in the short interval of the arc discharge, the repeatability of percussion welds is affected by variations in arc-starting behavior, and hence is related to the voltage used. Voltages near 450 volts are not usually selected, as small variations in the operating conditions could change the mechanism of arc starting.

The use of a nib or a high-frequency current pulse at low voltages greatly improves the consistency of arc starting. With close control of the welding conditions, the quality of welds produced in low-voltage systems can be uniformly high, with the incidence of defective welds often being 0.1% or less.

Arc starting ordinarily takes place just before the workpieces come into contact, at a separation of about 0.0002 to 0.0004 in., in low-voltage systems in which a starter nib is used. The discharge takes place across a gap of typically 0.010 to 0.030 in. in low-voltage systems in which a high-frequency pulse is used. In studies of percussion welding of workpieces 0.040 in. in diameter using a voltage of 1300 volts, the arc discharge began when the gap between workpieces was 0.004 to 0.006 in.

Sequence of Steps. In operation, first a capacitor (or bank of capacitors) is charged by direct current from a rectifier or motor-generator, and then one of the parts being welded is advanced toward the other and rapidly accelerated. When the two parts are close enough, the capacitor discharges and explodes the nib (arc starter), if one is used. The intense arc formed between the parts by the discharge heats the work surface of each part to the melting temperature in a fraction of a millisecond. Then, as one part is impacted against the other at high velocity, molten metal is expelled from the joint and the parts are forged together to complete a weld. The sequence of steps in capacitor-discharge percussion welding is shown in a simplified way in Fig. 1.

Control. Close control of voltage, capacitance, impact velocity and limiting resistance is important for producing a good weld. The voltage and capacitance determine the amount of energy stored in the system, and hence the heating capacity of the arc. Impact velocity (along with the mass of the moving workpiece and clamping members of the machine) determines the amount of forging energy. The limiting resistance generally is adjustable and controls the peak discharge current.

These four factors interact to determine the arc duration and the timing

with respect to arc discharge. The approach of the workpieces serves as a switch to trigger the arc discharge.

Usually, conditions are adjusted to give the shortest arc time that will permit consistent production of welds having the desired properties. If the parts being welded are forced together too soon, the arc is extinguished before the work surfaces of both parts are melted. If the impact is delayed too long after arc initiation, the melted interfaces may solidify too soon to permit expulsion of excess molten metal.

Preparation of workpieces for capacitor-discharge percussion welding varies widely, depending on the application. If a nib is needed for arc starting, a shear or cutter usually serves to produce the desired tip configuration.

Displacement, Current and Voltage. The changes in displacement of the moving workpiece, welding current, and voltage across the weld that take place during capacitor-discharge percussion welding, based on oscillograph records for the welding of wires, are shown schematically in Fig. 2.

Displacement of the moving workpiece in the direction of travel proceeds at a uniform rate during the arc discharge and while molten metal is being expelled, but is slowed as the forging action takes place. Displacement continues beyond the final displacement on the completed weldment because of deflection of the mechanical system and the workpieces. The maximum displacement because of deflection is reached after about 3 milliseconds, and the oscillations are damped rapidly, becoming insignificant after a reverse-oscillation peak that occurs after an additional interval of approximately 5 milliseconds.

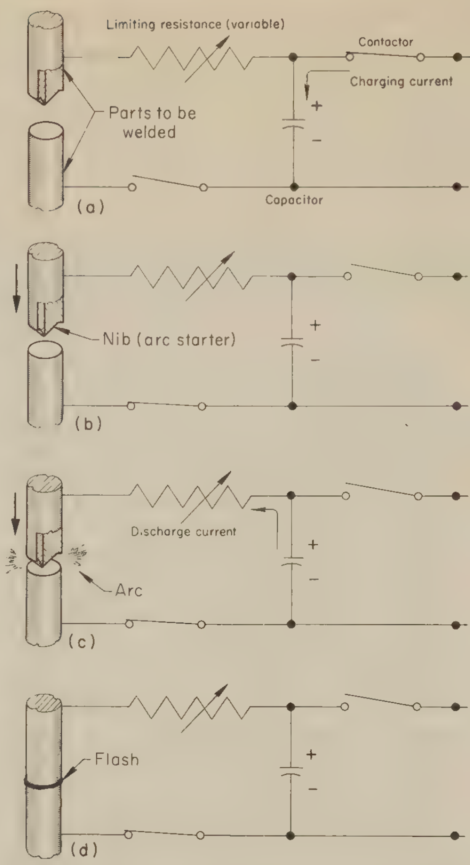
Peak welding current is achieved almost immediately on arc initiation, and the current then decays rapidly during the arc discharge. As shown in Fig. 2, the current increases to a secondary peak on contact of the workpieces, because of the sudden drop in electrical resistance, and then tapers off to zero in an additional 3 to 5 milliseconds.

Voltage across the weld decreases very rapidly to a fraction of its initial open-circuit value when the arc is initiated by the close approach of the moving workpiece to the stationary workpiece, and then decreases less rapidly as the arc discharge continues. When the arc is extinguished on contact of the workpieces, after a typical arc time of 0.25 to 1.15 milliseconds, the voltage decreases instantly to nearly zero.

The magnitude and rate of change of displacement, current and voltage vary with the size and nature of the workpieces and the characteristics of the welding equipment. Figure 2 is based on the welding of 0.015 to 0.040-in.-diam wire of various materials, including Dumet, nickel, nickel-plated steel, and copper-plated steel.

Low-Voltage Capacitor-Discharge Percussion Welding

Low-voltage capacitor-discharge percussion welding is done on many types of equipment. Simple and relatively inexpensive machines are used for low production (see the section on Low-Production Welding in Nib-Starter Machines, page 183). Commercially available and specially designed machines of widely varying capability, complexity and cost are used for welding in intermediate to large quantities, and generally can be adapted for use with specially designed work-handling equipment for semiautomatic or automatic high-volume production.



(a) Contactor is momentarily closed to charge the capacitor. (b) One of the parts to be welded is advanced toward the other and rapidly accelerated. (c) The arc forms across the gap just before the parts meet, melting the work surface of each part, and exploding the nib (arc starter), if one is used. (d) The arc is extinguished as one part is impacted against the other, expelling molten metal as flash and forging the parts together to complete the weld.

Fig. 1. Simplified representation of sequence of steps in capacitor-discharge percussion welding

The amount of energy stored in the capacitor bank to make a weld is usually regulated by selection of the number of capacitors charged and by charging to a controlled voltage. The initial-gap technique is used throughout. Except for machines that use a high-frequency pulse of alternating current for arc starting, the approach of the workpieces initiates the arc.

Machines for low-voltage capacitor-discharge percussion welding can be classified on the basis of the arc-starting technique as nib-starter and high-frequency-start machines.

Nib-Starter Machines. In one type of machine for low-voltage capacitor-discharge percussion welding, a nib is used for arc starting (see the section on Arc Starting). This machine usually consists of a portable power supply and either a hand-held gun or a bench-mounted welding head, but these components can also be built into a specially designed integral machine. Voltages of from 50 to 150 volts are usually employed for welding with the bench-mounted machine; for operator safety, the voltage used with the hand-held gun is ordinarily about 50 volts.

The bench-mounted machines and integral machines are readily adaptable to mechanization for high-speed, high-volume welding operations, but the hand-held gun has the advantage of portability. Otherwise, the machines operate in much the same manner.

The machines have two sets of jaws — one set movable and the other stationary — with provision for precise alignment of the two sets of jaws and for setting of the initial gap. One workpiece, usually a wire, is held in the movable jaws; and the second workpiece, usually a terminal, is held in the stationary jaws. Some hand-held guns are made to hold only the movable wire (workpiece); this type of gun is held against the stationary workpiece, and is suitable for welding to large, approximately flat workpieces. Wire size is about 0.006 to 0.100 in. in diameter; terminals are usually at least 0.006 in. thick.

When the switch is actuated, the wire moves toward the terminal at high velocity. Impact velocity varies with the wire size and the mass of the moving jaws, but is ordinarily between 80 and 150 in. per second (see the section on Welding Force, page 179). Total arc time is about 0.15 to 1.0 millisecond.

The basic electrical system for nib-starter low-voltage capacitor-discharge machines is shown schematically in Fig. 3. The limiting resistor controls the peak discharge current during welding. Another resistor is used as charging ballast, to limit the peak charging rate. Moving the switch to the welding position (as in Fig. 3) isolates the rectifier and charging circuit from the capacitor bank and discharge circuit. In repetitive welding, the switch remains in this position long enough for the weld to be completed, whereupon it is returned to the charging position to allow recharging of the capacitor bank. The switching is controlled automatically, often by a system of cams.

Nib-starter machines vary in details of construction and many are designed for specific welding applications.

The driving force for propelling one of the workpieces in such equipment is provided by springs, cams (or cams plus levers), or electromagnets. Timing is automatic for some or all machine functions. Rotating cams on a central shaft are often used to actuate switches, relays or other devices, as well as to provide machine motions directly. Solid-state timers or other types of timing devices are used in some machines.

Precise alignment is important; for example, when wires of 0.010-in. diameter are welded, a misalignment of 0.002 in. can reduce weld size and cause poor welds if wires deflect on impact.

Three examples in this article describe low-voltage capacitor-discharge percussion welding using nib-starter machines. A hand-held low-voltage gun

was used in Example 175 for welding of tinned copper leads to copper alloy 710 (copper nickel, 20%) terminals on a relay. A specially designed machine was used in Example 176 to join Dumet wire to molybdenum; cam drive was used to accelerate the Dumet wire in this operation. Another type of specially designed machine, with the driving force provided to the movable workpiece by an electromagnet, welded copper wire to a platinum-rhodium alloy in Example 177.

Production rate is usually limited by the time needed for loading and unloading the workpieces or for other work-handling operations. With manual loading and unloading, the production rate for a single welding head is often about 200 to 500 welds per hour.

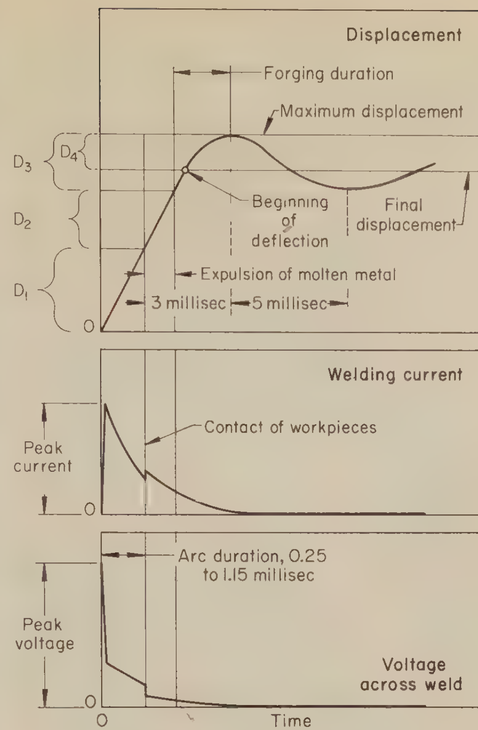
In fully mechanized welding, the repetition rate of the machine can become a limiting factor for the production rate in welds per head. The charging time for the capacitor bank usually is an approximate measure of the total weld cycle time, which can vary from about 0.2 to 1 sec or more, corresponding to production rates of 18,000 and 3600 welds per hour, respectively.

In Example 175, the production rate was 200 welds per hour with manual loading and unloading of a hand-held gun, but 12,000 welds were made per head per hour on similar parts in a fully automatic six-head machine. In Example 176, the production rate per welding head was 6000 to 10,000 welds per hour in a completely mechanized operation. Studs were fed from a vibratory feeder, and wire was fed from a spool and automatically cut off after each weld. In Example 177, 80 welds (40 assemblies) per hour were made in a bench-mounted machine with manual loading and unloading.

High-Frequency-Start Machines. In the second commonly used type of machine for low-voltage capacitor-discharge percussion welding, a high-frequency, high-voltage pulse of alternating current serves as an arc starter by ionizing the air in the gap between the workpieces. This machine, like the nib-starter machine, usually consists of a portable power supply and either a hand-held gun or a bench-mounted welding head. These components can also be built into a specially designed integral machine. Suitability for mechanization and arrangements for holding and aligning the workpieces in this machine are similar to the nib-starter machine.

The main application is in welding a wire to another wire, to a pin terminal or to a large flat surface. Solid wires about 0.100 in. to less than 0.005 in. in diameter, or stranded wires as small as 0.010 in. in over-all diameter (four strands of 0.004-in.-diam wire), are welded. Special provisions are made for damping the rebound on impact in welding the smaller-diameter wires.

This type of machine differs from the nib-starter type in the following respects: (*a*) there is no need to prepare a nib on the wire by an angle cut or other means, and the wire can be cut off square or in any convenient shape that gives reproducible dimensions; (*b*) timing of machine function is done with solid-state devices that have a switching time of 0.001 to 0.002 milliseconds; (*c*) the driving force to propel the moving workpiece is provided by a solenoid or electromagnet; and (*d*) the approach of the workpieces does not initiate the arc.



D_1 = Displacement during arc discharge
D_2 = Displacement during expulsion of molten metal
D_3 = Displacement during forging and deflection
D_4 = Displacement during deflection

Diagrams are based on oscillograph records made in studies on the welding of wires (see text). (Source: Irving Bradley, Use of Percussive Welding in Electronics, *Electro-Technology*, Sept 1968, p 72)

Fig. 2. Changes in the displacement of the moving workpiece, welding current, and voltage across a weld during capacitor-discharge percussion welding

A simple form of the high-frequency-start machine (system A) has a basic electrical system like that shown in Fig. 3, but with the limiting resistor replaced by an autotransformer, to which a solenoid and a high-frequency pulse generator (toroid) are connected in series. When the work has been loaded in the preset position with the desired gap, the operator closes a switch to make the weld. The switch (as in Fig. 3) moves to the weld position, closing the discharge circuit from the capacitor bank through the autotransformer and toroid to the weld gap. A high-frequency pulse bridges the weld gap during the first half-cycle of the pulse, ionizing the air in the gap. The arc discharge across the gap then starts, about 0.010 to 0.015 milliseconds after the operating switch is closed. The flow of current through the solenoid actuates it to propel the movable workpiece toward the stationary workpiece at high velocity. Total time elapsed at the beginning of the forging action is typically 1¼ to 2 milliseconds.

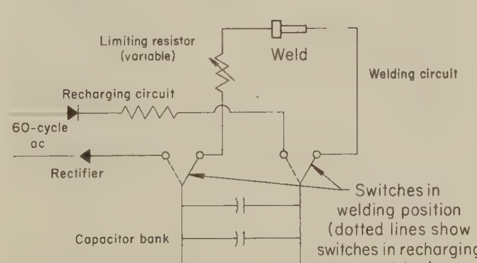


Fig. 3. Basic electrical system for nib-starter low-voltage capacitor-discharge percussion welding machines (typical)

Contact of the parts extinguishes the arc. The switch remains in the weld position for a total time of about 6 to 15 milliseconds, to allow completion of the weld and nearly complete decay of the welding current and voltage, and then automatically moves to the charge position. The capacitor bank is then recharged by the rectifier to the desired preset voltage, and the machine is ready to repeat the welding operation, after a total time of 1.5 sec or less for a complete welding sequence.

The major fraction of the weld cycle time is the charging time, which depends on the characteristics of the charging unit and the capacitor bank and the amount of energy in the charge. Maximum charging time for the type of equipment described is less than 1.5 sec.

In this form of high-frequency-start machine, two basic adjustments are used to optimize weld properties. Heat input to the weld is adjusted by selecting the number of capacitors to be charged and setting the charging voltage. Impact velocity (and timing) is adjusted by setting the gap. However, the adjustment of heat input also affects impact velocity (and timing) by changing the amount of current passed through the solenoid. Thus, heat input and impact velocity (and timing) cannot be changed independently by routine adjustments.

A more versatile form of the high-frequency-start machine (system B) has greater capacitance and has the solenoid, heat input and arc initiation independently powered. Thus the high-frequency pulse can be timed to occur at some definite point during workpiece travel. The independent control of arc initiation, heat input and impact velocity thus provided gives system B greater flexibility in balancing the heating effect at the weld against the forging action. This feature, and the greater capacitance, makes it possible to weld a wider range of sizes of wire with system B. A comparison of characteristics of the two systems, and of diameters of wire that can be welded by each system, is as follows:

	System A	System B
Capacitance, max .	800 mfd	4000 mfd
Solenoid connection	Series	Parallel
Voltage, v	12-75	12-120
Gap, in.	0.008-0.010	0.015-0.020
Wire diam, in.	0.015-0.070	0.004-0.102

System B allows a greater variety of metal combinations to be welded.

Intermediate and High-Production Welding in Nib-Starter Machines

The equipment and techniques described for low-voltage capacitor-discharge percussion welding have many applications in joining wire leads to

wires, pins or terminals in the telephone, electronics, electrical equipment, and lamp industries. Three applications involving different workpiece materials, variations in equipment design and operation, and different production rates are described in the three examples that follow. The first of these describes the welding of tinned copper leads to copper alloy 710 (copper nickel, 20%) terminals on a relay, using a hand-held gun for a production rate of about 200 welds per hour. Although copper can be readily brazed to copper alloys, the manufacture of terminal boards precludes the use of a heat input as great as that needed for brazing. The intense but localized heat in percussion welding penetrates only a few thousandths of an inch into the workpieces and melts the mating surfaces without producing a significant heat-affected zone.

Example 175. Capacitor-Discharge Percussion Welding of Tinned Copper Leads to Copper Alloy Terminals on a Relay (Fig. 4)

Leads made of 0.020-in.-diam annealed and tinned copper wire, which was insulated, were capacitor-discharge percussion welded to copper alloy 710 (copper nickel, 20%) terminals on a relay, in the setup shown in Fig. 4 and under the conditions shown in the accompanying table. In this arrangement, the copper wire was connected to the positive terminal.

The gun was a low-voltage, hand-held, motor-operated type and functioned in two stages. In the first stage, the stripped end of the copper wire was positioned in the wire jaw, with the insulation against the outer surface of the jaw, as shown in Fig. 4. The wire was then clamped, and the gun was cocked. The terminal jaw of the gun was then placed over a terminal; the initial gap between the wire and the terminal was 0.040 to 0.050 in. (Fig. 4). The weld was completed in the second stage by triggering the gun and thus actuating the driving force and completing the welding circuit to the workpieces.

A featheredge formed on the end of the wire by the use of a special cutter, as shown in Fig. 4, was used to start the arc as the wire approached the terminal.

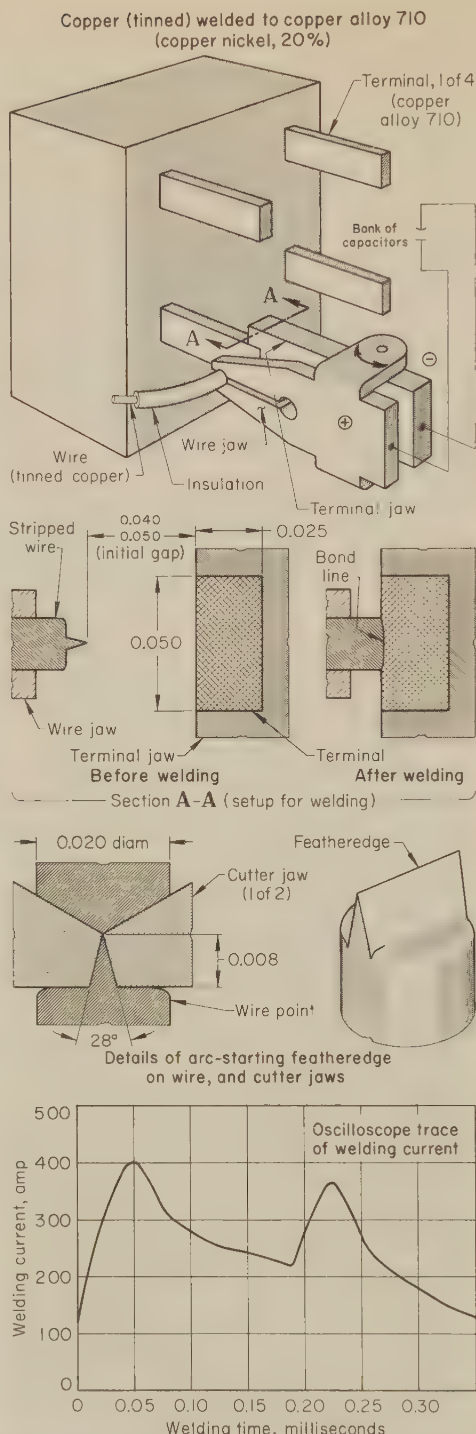
An oscilloscope trace (Fig. 4) of the capacitor discharge during welding showed a peak current of about 400 amp at about 0.05 millisecond after initiation. A second peak of about 350 amp occurred at about 0.22 millisecond, or just after the arc had been extinguished by full contact of the wire and the terminal.

The melted layer produced on the lead and the terminal at the joint and expelled from the interface by the forging action was 0.005 to 0.015 in. thick. The heat-affected zone on each side of the bond line in the completed weld was typically 0.002 to 0.003 in. deep.

Weld strength was tested in two ways. A straight pull, at 90° to the terminal, usually broke the wire outside the weld area. When the wire was bent 90° and pulled parallel to the terminal (pull-bend test), the breaking load was about 1 lb less than the wire strength.

The same technique, except that the welding was done with either a hand-held gun or a fully automatic bench-mounted welding head, was used in percussion welding of copper wires (component leads) 0.006 to 0.102 in. in diameter to terminals of copper, brass, tinned brass, nickel-silver, aluminum, low-carbon steel, or high-carbon steel that were 0.006 in. thick or thicker.

Depending on the size and composition of the parts being welded, capacitance ranged from about 500 to 50,000 microfarads at an operating voltage of 50 volts, which was preferred over high voltage for safety and better control of welding-energy input.



Power supply	Bank of capacitors
Gun	Hand held(a)
Capacitance	2000 mfd
Voltage	50 v
Initial gap	0.040 to 0.050 in.
Velocity of wire	90 to 100 ips
Arc time	Approx 0.2 millisecond
Welding force	3 lb
Melted layer(b)	0.005 to 0.015 in.
Energy per weld	2.5 watt-sec
Energy density(c)	8000 watt-sec/sq in.
Production per hour	Approx 200 welds

(a) Low-voltage, motor-operated gun. (b) Combined thickness of the melted layer on the wire and the terminal, which was expelled from the weld interface ("burn-off" or "meltback"). (c) Computed for the area of the weld.

Fig. 4. Setup for capacitor-discharge percussion welding of a tinned copper wire to a copper alloy relay terminal for conditions in table, details of arc-starting featheredge on the wire, and oscilloscope trace of welding current (Example 175)

The copper wire, because of its high thermal conductivity, was connected to the positive terminal in these applications. The heat-affected zone on each side of the bond line was typically 0.002 to 0.003 in. deep, with an extreme range of about 0.0015 to 0.008 in.

No special cleaning was required. Production per hour varied from about 200 connections per gun for manual operation to about 72,000 connections when using a fully automatic bench-mounted machine that had six separate welding units to make six welds at once. Charging time for the capacitor banks was about 0.2 sec.

When dissimilar metals with widely different melting temperatures are capacitor-discharge percussion welded, the relatively high heat input to the joint can produce a large amount of upsetting. These metals are usually difficult to join by other welding processes, because the metal having the higher melting point may not melt or alloy with the metal having the lower melting point. Percussion welding minimizes this difficulty, because of the almost immediate localized input of welding heat.

In the following example, wires of molybdenum and Dumet (copper-clad 58Fe-42Ni) were capacitor-discharge percussion welded in a high-production operation (350 million assemblies per year). This was the combined output from a number of fully automatic machines, each of which made 6000 to 10,000 welds per hour, averaging about 500,000 welds per machine per week.

This combination of wires is difficult to weld with reliability by other welding processes because of the difference in melting temperatures of molybdenum (4730 F) and the Dumet core (2900 F).

Example 176. High-Production Capacitor-Discharge Percussion Butt Welding of Molybdenum and Dumet Wires (Fig. 5)

The molybdenum wire stud and the Dumet (copper-clad 58Fe-42Ni) wire lead shown in Fig. 5 were capacitor-discharge percussion butt welded under the conditions shown in the accompanying table. The copper cladding on this size of Dumet wire was about 0.001 in. thick (17 to 26% by weight of the wire).

The welding machine, which was of special design, had a six-station rotary table that included one welding station. All the machine motions and electrical contacts were controlled by cams. The studs were fed automatically to the welding machine from a vibratory feeder. A wire-feeding device fed the Dumet wire from a spool, through a guide tube, and past a cutoff blade. Production was 350 million assemblies per year, using a number of these special welding machines.

The steps in welding were as follows:

1 Studs were fed from the feeder through a tube to the machine.
2 A stud was gripped by clamp jaws and held in position for welding.
3 Dumet wire from the spool was impacted into the stud, welded and cut off to a length of 1.605 ± 0.010 in. for the weldment of wire plus stud, and at an angle of 28° to 30°, as shown in Fig. 5. The cutoff provided a nib for the next weld.
4 A pickup arm removed the welded assembly from the clamp jaws and dropped it into a chute leading to an inspection area. The same pickup arm discarded assemblies joined by potentially weak welds on signal from a weld discriminator.

The depth to which the Dumet wire was heated in welding provided a relatively large amount of plastic metal. This metal was upset in welding and, as a result, the weld diameter was nearly equal to the diameter of the molybdenum stud, as shown in the welded assembly in Fig. 5. In the completed weld, the weld metal layer was only a few millionths of an inch thick. The heat-affected zone in the molybdenum was typically about 0.00001 in.; that in the Dumet was about 0.025 in. Sound welds could not be made at the production rates used unless the heat-affected zone in the Dumet was at least 0.018 in.

After welding, an inspector removed the assemblies that had welds with visible defects such as spikes, overwelds or heavy carbon deposits. In addition, electronic weld discriminators that monitored voltage versus current wave patterns inspected each assembly during the welding operation and automatically removed the workpieces that had potentially weak welds.

Weld quality was then tested on a random basis by 10-lb axial loading, which the welds had to withstand, and a bend test in which the assembly had to survive six bend cycles for satisfactory evaluation.

Figure 5 shows the setup for the bend test. The molybdenum stud was chucked into a fixture that could be turned to stress the weld. A 1-lb weight was suspended on the Dumet lead wire and the fixture was then rotated 90° (Fig. 5), to the bend position. Returning the fixture to the starting position completed one bend cycle. A frequency distribution for the number of bends to failure for 566 welded assemblies in a sample lot of 567 assemblies is given in Fig. 5. (One of the workpieces failed in the wire, instead of at the weld.) This distribution, which is typical of other sample lots, illustrates normal performance.

An acceptable quality level (AQL) of 0.5% and a 1% LTPD (lot tolerance per cent defective) plan were enforced.

Mechanical testing was supplemented by microscopic examination of etched sections through welded joints, at a magnification of 1300 diameters.

In the following example, capacitor-discharge percussion welding produced a reliable and inexpensive joint between wires having different diameters and melting points. A specially designed bench-mounted machine was used with manual loading and unloading for a production rate of 40 assemblies (80 welds) per hour. Driving force for the movable workpiece was provided by an electromagnet.

Example 177. Capacitor-Discharge Percussion Butt Welding of a 60Pt-40Rh Wire to Copper Wires (Fig. 6)

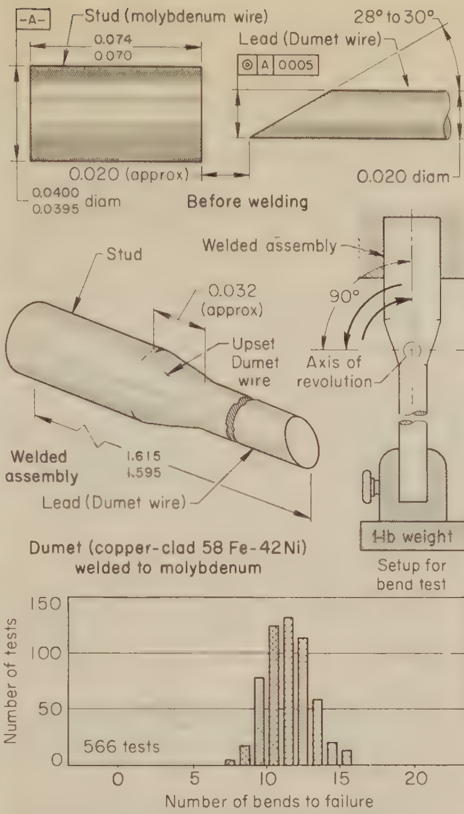
Both ends of a 0.020-in.-diam annealed 60Pt-40Rh wire were capacitor-discharge percussion butt welded to 0.040-in.-diam hard drawn and tinned copper wires 0.50 in. long, in the assembly of the resistance brazing tip shown in Fig. 6(a). The ends of the copper were cut off square, and the Pt-Rh wire was cut at an angle to provide a nib at each end to start the arc. (The brazing tip was used to resistance braze fine copper wires to copper terminals, as described in Example 603 in the article on Resistance Brazing in this volume.) Figure 6(b) shows the welded assembly.

A diagram of operating fundamentals of the welding machine is shown in Fig. 6(c). The electrical circuit included the wires to be welded, two sets of gripper jaws and an electromagnet. The sets of gripper jaws held the wires in alignment for welding. One set of jaws was mounted on an adjustable carriage having a manual advance mechanism, and the other set was mounted on an armature, or lever, that was moved by the electromagnet when it was energized. The gap between the electromagnet and the armature was 0.010 in.

Power was supplied from a bank of capacitors that could be charged to a preselected energy level at a potential of 30 to 80 volts and had a maximum capacitance of 3000 microfarads. The capacitor bank was charged with direct current from a rectifier that drew a current of 2 amp from the 115-volt, 60-cycle alternating-current power line.

In operation, jaws mounted on the adjustable carriage clamped a precut length of 60Pt-40Rh wire so that it extended 1/16 to 3/32 in. beyond the jaws. This wire had positive polarity for the welding operation. Another set of jaws clamped a precut length of copper wire so that it extended 1/8 in. beyond the jaws. The carriage then was advanced to bring the ends of the wires together, striking an arc between them.

As the capacitors, which had been charged to a preselected energy level, discharged through the arc, the arc caused meltback of the wires, and the flow of current through the electromagnet (see Fig. 6c) energized it. The energized electromagnet then closed the gap between it and the armature, and impacted the Pt-Rh wire against the copper wire to complete the weld.



Welding machine	Special design(a)
Input power to charging unit	20 to 50 watts(b)
Capacitance	4000 mfd
Welding current	200 amp
Voltage	50 v
Initial gap	0.020 ± 0.005 in.
Driving force, max	Approx 2.0 lb
Welding force	1 to 2 lb
Energy per weld	5.0 watt-sec
Energy density	16,000 watt-sec/sq in.
Arc time	2 milliseconds
Production per hour	6000 to 10,000 assemblies
Production per year	350,000,000 assemblies(c)
Cost per 1000 assemblies	Approx $2.50

(a) Equipped with a six-station rotary table, including one welding station (see text); single-station automatic machines were also used, with suitable modification of procedure. (b) Single-phase, 60-cycle alternating current. (c) Using a number of machines, most of which were single-station machines, all at about the same hourly production rate.

Fig. 5. Molybdenum wire stud and Dumet wire lead that were capacitor-discharge percussion butt welded, setup for bend test of welded assemblies, and frequency distribution of bends to destruction for 566 assemblies (Example 176)

The subassembly was removed from the gripper jaws and reversed end-to-end to make the second weld. A second length of copper wire was clamped in the jaws at the right in Fig. 6(c) and the Pt-Rh wire of the subassembly was clamped in the jaws of the carriage. The procedure used to weld the subassembly was then repeated to produce the assembly shown in Fig. 6(b).

Weld quality was then tested by manually bending the welded assembly near each joint, through a 90° bend. If the weld was not acceptable, machine settings were adjusted and the wires were rewelded, until acceptable welds were made. This method of determining proper machine settings was used because production quantity was small.

After welding, the assembly was manually bent to a U-shape (Fig. 6a).

The depth of the heat-affected zone on either side of the bond line was 0.005 in. or less. The total energy used in making one weld was approximately 8 watt-sec. Arc time per weld was about 0.1 millisecond. Production rate was 40 assemblies per hour.

Low-Production Welding in Nib-Starter Machines

The simplest type of low-production percussion welding equipment uses a nib for arc starting and has a gravity-operated cantilever arm, which is pivoted on a low-friction bearing, to provide the welding force. A machine of this type, which was built from commercially available electrical and mechanical devices by the user for welding of metallographic specimens, is described in Example 178.

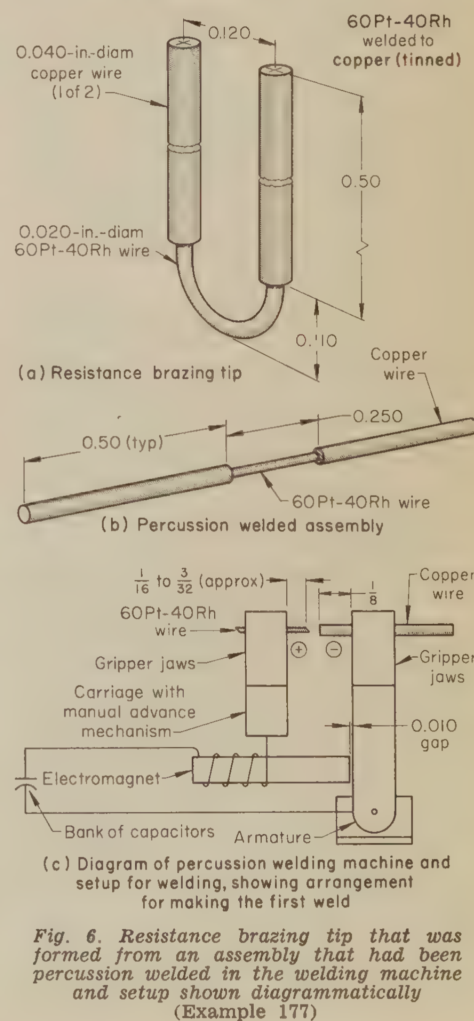


Fig. 6. Resistance brazing tip that was formed from an assembly that had been percussion welded in the welding machine and setup shown diagrammatically (Example 177)

Another user-built machine of this general type was used to weld wires of various materials and sizes for electronics applications. The versatility of this simple machine is illustrated in Table 2, where the conditions and results for welding seven combinations of work metals are given.

The circuit was essentially like that shown in Fig. 3. The power for welding was supplied from a bank of 20 electrolytic capacitors rated at 20 microfarads each and 600 volts max. The capacitors were connected in parallel for a total capacitance of 400 microfarads, arranged so that all or a fraction of the bank could be used, as desired. The limiting resistor was a stepless 0 to 7.5-ohm, 50-watt potentiometer. A rectifier rated at 0 to 500 volts and 100 milliamp max was used to charge the capacitor bank.

The movable workpiece was held in a pin vise mounted on a gravity-operated cantilever arm, which pivoted on a low-friction bearing. Effective weight of the cantilever was 6 oz, but additional weights could be added if needed. Precise alignment of the workpieces for welding was accomplished by positioning the lower workpiece with the aid of a compound table having screw-operated travel in two directions, while observing the workpieces through a magnifying glass. Cutting the wires (the workpieces) with ordinary wire cutters produced a chisel-type tip, which functioned as an arc starter.

Excellent welds were obtained on difficult-to-weld metal combinations, as shown in Table 2. In addition, this equipment provided the capability of welding precisely located wires in areas with limited accessibility.

Percussion welding machines like that just described, although not efficient for medium or high production, can perform many joining operations on small parts that would be very difficult, time consuming, or costly if performed by other means.

Example 178 describes the percussion welding of a 0.032-in.-diam type 304 stainless steel support wire to a typical metallographic specimen of Inconel 600. The equipment, which was assembled by the user, and the procedure described were used also in welding stainless steel support wires to metallographic specimens of many different shapes, sizes and metals, including titanium and zirconium. The welding of stainless steel wires to all metals tried over a period of several years was successful. This technique can also be used for joining a lead wire for electrolytic etching to a metallograph specimen after mounting the specimen in plastic.

Limited heat input is important in this application, in which the microstructure of the specimen had to be kept unchanged well away from the surface to be examined.

The machine was designed and built by the user from readily available mechanical and electrical equipment. The mechanism supporting the welding head was a standard part of a commercial percussion welder. Other advantages were that little or no operator skill was required, and that the time for setting up and welding a specimen was typically less than 1 min.

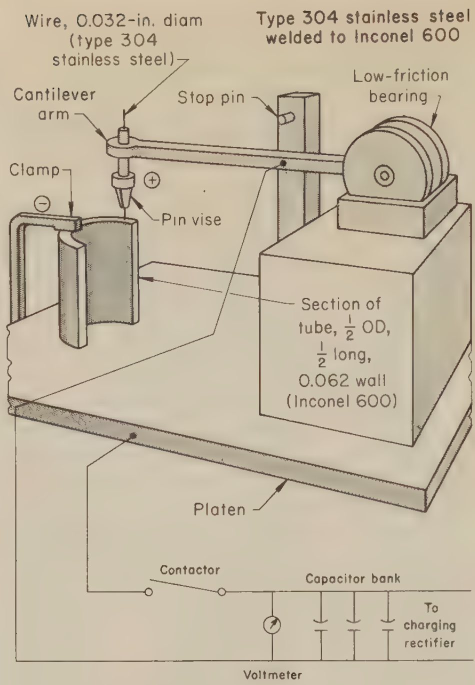


Fig. 7. Setup for capacitor-discharge percussion welding of a type 304 stainless steel support wire to an Inconel 600 metallographic specimen (Example 178)

Example 178. Capacitor-Discharge Percussion Welding of a Stainless Steel Support Wire to an Inconel Specimen (Fig. 7)

Figure 7 shows the setup for capacitor-discharge percussion welding of a 0.032-in.-diam type 304 stainless steel wire to a section of a 0.062-in.-wall Inconel 600 tube that was ½ in. in outside diameter and ½ in. long. The tube section was to be nickel plated to protect the edges during subsequent polishing for use as a metallographic specimen, and the wire provided support and electrical connection for the electroplating operation.

A gravity-operated cantilever arm, which pivoted on a low-friction bearing and was supported by a stop pin (Fig. 7), was a standard part of a commercial percussion welding machine and provided the welding force. The starting height could be adjusted to change the velocity and impact momentum. A pin vise mounted to the cantilever arm held the wire above the tube.

The power-supply unit was a 1200-microfarad, 450-volt bank of capacitors, which was charged to about 75 to 100 volts by a rectifier (not shown). Closing the arc-resistant contactor shown in Fig. 7 energized an electromagnet (not shown), withdrawing the stop pin and allowing the arm to drop. Closing this contactor also opened a switch between the charging rectifier and the capacitor bank, and completed the discharge circuit from the capacitor bank to the two workpieces, permitting the arc discharge to take place at the correct interval before impact.

The stainless steel wire had positive polarity for the welding operation. The wire was cut with hand wire cutters in preparation for the welding operation. The cutters produced a chisel-shape tip on the wire, which acted as an arc starter. The shape of the tip was not considered to be critical.

The static weight of the cantilever arm, measured at the point where the wire was held, was 57 grams. The arm was positioned to drop the wire about ⅛ in. The charge on the capacitors was 75 to 100 volts. Melting of the end of the stainless steel wire was so slight that no flash was evident around the wire.

In operation, the tube was manually positioned and clamped, because positioning of the wire was not critical. The charging time on the capacitors (and, hence, the voltage) was adjusted to change the energy input to the specimen until a visually good weld was obtained. Operators did not need special skill or experience. The total time for setting up and welding a specimen was typically less than 1 min.

The welded joint was strong and had good electrical conductivity. The heat-affected zone was very small, and thus the microstructure of the specimen was unchanged a few mils from the weld.

High-Voltage Capacitor-Discharge Percussion Welding

High voltage, usually 1000 to 3000 volts (but occasionally up to about 6000 volts), is used only in bench-mounted machines or specially designed integral machines for capacitor-discharge percussion welding. The difficulty and expense of providing protection for the operator against high voltage precludes the use of hand-held guns in high-voltage systems.

Applications are similar to those described for low-voltage welding, but the diameter of the smaller workpiece in high-voltage production welding does not ordinarily exceed about 0.060 in. (compared with about 0.040-in. diameter in low-voltage systems). Maximum diameter of the smaller workpiece is about 0.70 in. (compared with about 0.10 in. in low-voltage systems). No nib or other arc-starting aid is needed; the tip of the moving workpiece can have any convenient shape.

The welding operation is generally very much like that described for nib-starter machines in the section on Low-Voltage Capacitor-Discharge Percussion Welding (page 180), and the basic electrical system is like that shown schematically in Fig. 3.

The amount of energy stored in the capacitor bank to make a weld is usually regulated by selection of the number of capacitors charged and by charging to a controlled voltage. The initial-gap technique is used throughout, and the approach of the workpieces initiates the arc discharge. Impact velocity in high-voltage welding is typically about 40 in. per second for wire 0.040 in. in diameter.

The machines are usually of special design to suit the application, and are intended for semiautomatic or fully automatic operation in intermediate to high-production welding.

In fully mechanized systems, charging time for the capacitor bank may be a limiting factor for the number of welds made per minute by a single welding head. A charging time of 300 milliseconds, corresponding to a maximum production rate of 120 welds per minute for a single welding head and capacitance of 75 to 240 microfarads, is typical.

Some machines are fitted with more than one welding head, each with its capacitor bank, to increase production rate. Each capacitor bank is recharged during loading and unloading time.

The example that follows describes the high-voltage capacitor-discharge percussion welding of electrical contacts to connector wires in high-speed automatic production, using a programed-feed dual-head machine.

Example 179. Programed High-Voltage Percussion Welding of Three Types of Electrical Contacts to Closely Spaced Connector Wires (Fig. 8)

Copper alloy 715 (copper nickel, 30%) electrical contact blocks were percussion welded to 0.040-in.-diam copper alloy 770 (nickel silver, 55-18) wires by high-voltage capacitor discharge in specially designed high-production automatic welding equipment. In welding, a contact block, 0.101 by 0.073 by 0.042 in., was propelled against the square-cut end of a connector wire, attaching the face of the block to the wire end.

Percussion welding was selected because it permitted minimal heat input to the joint, avoided problems in heat balance from the size difference between the workpieces, was compatible with the close spacing (0.110-in. centers) of the wires, and, because of its short repetition time, was suitable for high-speed automatic machines.

The machine was built and put into service before the development of low-voltage capacitor-discharge techniques for percussion welding, and has been used for this welding application for more than 15 years with excellent results. This high-voltage operation has had the advantages of simplicity of operation, high reliability of welds, and operation without an arc starter on the end of wires or by using a high frequency current.

Figure 8 shows the welded assembly, which was part of a telephone-type wire-spring relay. Contact blocks were welded to the square-cut ends of some or all of the 12 nickel silver connector wires, which projected about 0.200 in. from their encasing phenolic frame; two wires received no contact blocks in the assembly shown.

A contact block and connector wire in position for welding, and a completed weldment, are shown in Section A-A of Fig. 8, and the design details of the three different types of contacts used in a single assembly are also shown in Fig. 8. Contact blocks with palladium on both top and bottom were used as "transfer" contacts in the operation of the relay; those with palladium on either the top or bottom only, as "make" or "break" contacts, respectively.

All welding-machine functions were controlled and actuated through a main drive and camshaft. Phenolic block – wire subassemblies (workpieces) were moved along a straight-line conveyor to the welding station, with the wires horizontal and at 90° to the direction of travel.

The machine had two welding heads, arranged side-by-side, spaced on 0.720-in. centers, that made welds simultaneously. One welding head made the welds on wires 1 to 6; and the second, on wires 7 to 12 (see view of welded assembly in Fig. 8).

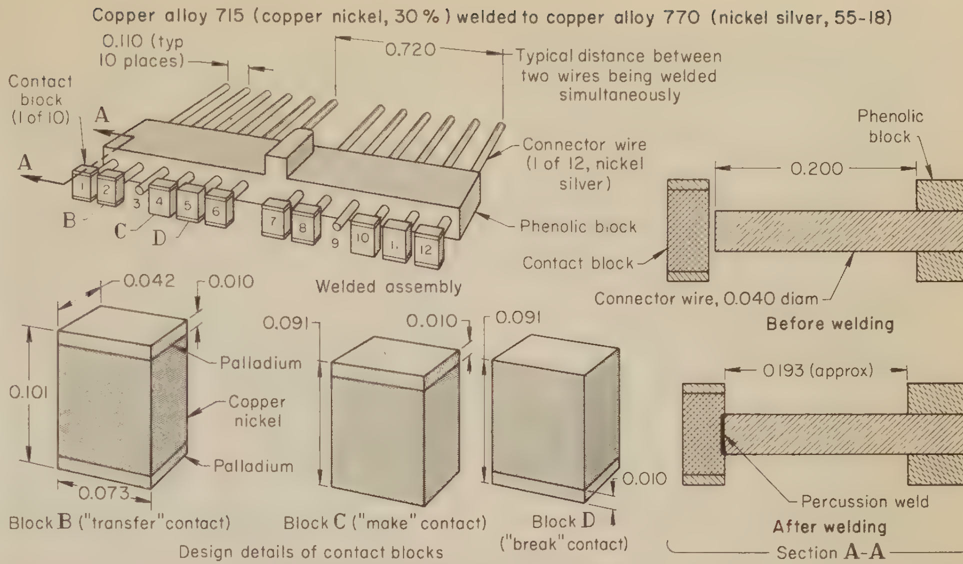
At each cycle of the machine, the workpiece at the welding station was stepped along to move the next wire into welding position. At each cycle during which a weld was to be made, a contact of the type specified for the wire at the welding position was fed into welding position in each welding head.

A selective hitch-feed mechanism for each head fed contact tape to an automatic cutter, according to a preset program for the relay, from one of three reels that contained coils of the three types of contact material. No tape was fed to the cutter for wires that were not to receive a contact.

At each cycle, transfer fingers operated to move a contact from the cutter to the load position, and to move a contact from the load position to the weld position (jaws of the welding head). One contact-cutting-and-feeding mechanism served the welding head for wires 1 to 6; and a second, the welding head for wires 7 to 12.

In making a weld, the jaws holding a contact were released from the cocked position by cam action and propelled toward the wire by a spring. Velocity at impact was about 40 in. per second. The mass of 30 grams (jaws plus contact block) produced an impact force of about 30 lb.

Welding power was supplied to each welding head directly from a 75-microfarad



Welding machine	Special design(a)	Arc time	0.1 to 0.4 millisecond
Capacitance	75 mfd	Burn-off, total	0.005 to 0.010 in.
Voltage	1300 v	Heat-affected zone	0.001 to 0.002 in.(c)
Initial gap	0.150 in.	Breaking load of weld	150 to 160 lb
Velocity at impact	40 ips	Charging time	Approx 0.3 sec
Welding force	Approx 30 lb(b)	Production rate	120 welds per minute(d)

(a) Dual-head, cam-controlled from main drive shaft; selective automatic cutoff and feed of contact blocks from three reels of different contact stock (see text). (b) Mass of moving jaws and workpiece was 30 grams. (c) Including a maximum thickness of about 0.001 in. of weld metal. (d) For each of the two welding heads.

The machine automatically cut the contacts from coiled "tape" of three different types, and fed contacts and wire subassemblies to a dual-head welding machine in a programed sequence to produce the desired arrangement of contacts. The machine also was programed to omit the welding of contacts to specified wires.

Fig. 8. High-voltage percussion welded assembly of copper nickel – palladium contacts to closely spaced nickel silver connector wires mounted in a phenolic block for a telephone-type relay, and details of joint and the three types of contacts (Example 179)

capacitor charged to a potential of 1300 volts. As the contact block approached the wire, an arc was established between them at a gap of a few thousandths of an inch. Portions of the abutting surfaces of both the wire and the contact base metal were melted and expelled from the arc zone before the molten surfaces were forced together in firm contact. (Normally, the total amount of metal melted and expelled is 0.005 to 0.010 in.)

Arc time was 0.1 to 0.4 millisecond. Nearly all the heated metal was expelled from the joint during the welding operation, so that a heat-affected zone of about 0.001 to 0.002 in. remained.

Welds were made at the rate of 240 per minute, 120 per minute for each welding head and capacitor. Each capacitor was charged for each weld by a separate thyratron-tube rectifier; the two rectifiers operated from a common source of high-voltage current. The charging time was approximately 0.3 sec.

With routine control of the operating conditions in production, the welds were highly reliable. Less than 0.1% of the relays produced had unacceptable welds.

Visual examination for defective welds was made in production by the machine operator. In addition, the retraction of the welding-head jaws from a welded contact block exerted a pull of 2 lb on the block, thus providing a check for very weak welds or unwelded contact blocks.

Weld strength was tested on a statistical sampling of production welds with a "hook-pull" gage, which applied a combined tension and bending force to the weld. Samples tested in straight tension for comparison showed that a hook-pull force of 50 to 60 lb was equivalent to 150 to 160 lb of straight tension. In the tension samples, failure occurred more frequently in the wire than in the weld.

Protection for personnel against high voltage was provided in the machine by door interlock switches, solenoid-release shorting bars, and bleeder resistors on the capacitors. Safety from mechanical jams was provided by a slip clutch on the main drive and by a pull-out clutch and automatic stop switch in the transfer drive mechanism for the block – wire assembly.

Magnetic-Force Percussion Welding

In magnetic-force percussion welding, a resistance welding transformer supplies the welding current at a voltage of about 10 to 35 volts. This transformer has lower impedance and higher secondary voltage than the transformers ordinarily used in resistance welding. The system functions like a low-voltage direct-current system without an auxiliary energy-storage device, because the weld is made during the first half-cycle of current flow of a 60-cycle alternating current.

Welding force is developed by an electromagnet, and the magnitude of this force, which is controlled by a separate transformer, can be varied without affecting the welding current. The welding force needed depends on the size and composition of the parts being welded, as these determine the response of the parts to heating.

The arc starter usually is a nib or a projection on one of the parts to be welded. For welding elongated parts, two nibs are sometimes necessary. An air cylinder holds the workpieces together at low pressure while a current path is established through the nib.

A magnetic-force percussion welding machine is similar to a press-type

resistance welding machine. Figure 9 shows a diagram of the machine. The six-step sequence of operations in welding in this machine is given in Example 180 below.

The diameter and height of an arc-starting nib or projection depend on the application. The diameter must be large enough to prevent the nib or projection from collapsing under the initial pressure, but it must not be large enough to permit the nib or projection to carry the welding current. The height determines the gap between the workpieces to be welded and the arc voltage that is necessary to explode the nib.

Arc time is up to 8 milliseconds, and is governed by the amount of energy discharged, the magnitude of the magnetic force, and the dimensions of the arc-starting nib. The interval between initiation of the arc and application of the magnetic force has an influence on the arc time and also on the resulting weld quality.

Weld areas of 0.04 to 0.70 sq in. can be welded in production. Some meltback (besides the explosive removal of the nib) occurs at the weld interface and, in most applications, some flash must be removed. Weld metal is not always completely expelled from the joint (see Example 180).

Applications. Magnetic-force percussion welding is used in joining silver – cadmium oxide to brass, cadmium-plated brass or copper; copper to copper; copper to silver-tungsten; and copper to silver – cadmium oxide (see Example 180).

One manufacturer uses this process for joining tungsten and molybdenum tips to RWMA class 2 copper shanks in making resistance welding electrodes, to extend the useful temperature range at which they can be used. Electrodes 0.482 and 0.625 in. in diameter have been made in this way, instead of by the customary brazing method.

In the following example, a change was made from brazing to magnetic-force percussion welding, to improve joint integrity and to prevent an undesirable annealed structure in an electrical-contact assembly. Production was 60 welds per minute for automatic, dial-feed welding, and 7 welds per minute for manual loading and unloading.

Example 180. Change From Silver Brazing to Magnetic-Force Percussion Welding for an Electrical Contact Assembly (Fig. 9)

Originally, two silver – cadmium oxide contacts and a copper backing strip were silver brazed, to make part of a switching device used in electrical equipment. A contact and the copper backing strip are shown in Fig. 9. Processing was changed to magnetic-force percussion welding because (*a*) the brazed joint, even for the best brazing conditions, contained voids, and (*b*) the comparatively large heat input in brazing produced an undesirable annealed structure in the workpieces. The percussion welded joints, which had a weld bond covering more than 80% of the mating surfaces, had good electrical and mechanical properties, and the properties of the welded assembly immediately adjacent to the bond line were unaffected by the heat input in welding.

In addition, the production rate by percussion welding was 4 times (using manual feed) or 36 times (using automatic feed) that by resistance brazing, the faster of two previously used silver brazing methods.

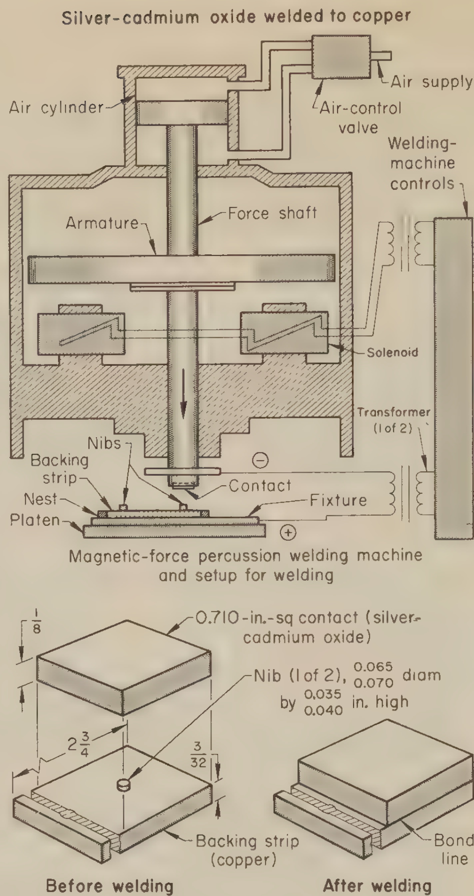


Fig. 9. Silver – cadmium oxide contact and copper backing strip that were magnetic-force percussion welded in the machine and setup shown (Example 180)

The percussion welding rate was 10 times (manual) or 90 times (automatic) that by induction silver brazing.

Before welding, two nibs (arc starters) were coined into the copper strip, as shown in Fig. 9. One nib was used in welding each contact. Each nib was located on the backing strip so that it would touch the center of a contact at the start of welding.

The copper backing strips were given a flash plating (0.0002 in. max) of tin shortly before welding. The silver – cadmium oxide contacts were received clean, in sealed cans. If difficulties occurred, the contacts were dipped in dilute hydrochloric acid or in hydrochloric-nitric acid and then thoroughly rinsed in hot and cold water.

The welding machine and setup for welding the first contact to the backing strip are shown in Fig. 9. The machine had two transformers. One supplied the welding current; the other supplied current to the solenoid that applied the welding force. Air pressure in the air cylinder applied the force to bring the contact against the nib on the backing strip and an initial low force to hold it there. Both the initial force and the welding force were applied through the force shaft. The fixture was of class 12 electrode material (copper-tungsten). An automatic dial feed was used, or loading and unloading were done manually.

The sequence of operations in welding each contact was as follows:

1 A contact and backing strip were securely clamped in position in the machine.
2 The start button was pushed, to initiate the welding cycle and automatically actuate and time the next three operations.
3 The contact was brought against the appropriate nib on the backing strip, by the force shaft, and initial force was applied to hold it there.
4 The flow of the welding current was started, the nib disintegrated and arcing spread across the interface.
5 The solenoid was energized and produced a high synchronized force on the force shaft, which closed the gap and exerted the welding force on the parts being joined.
6 The welded assembly was removed from the machine.

Steps 2 through 5 were interlocked so that (after the initial force had been applied and the welding current had been started) the solenoid actuated the force shaft at approximately the time the arc was initiated. Welding voltage was 20 to 30 volts, and maximum current was 100,000 to 125,000 amp.

In welding, a total thickness of about 0.010 in. was melted at the interface of the workpieces and expelled from the joint, usually in approximately equal amounts because the two materials have the same conductivity and do not differ greatly in melting temperature. Thickness of weld metal remaining in the completed joint did not ordinarily exceed 0.005 to 0.007 in. The heat-affected zone in the copper backing strip had a maximum thickness of about 0.005 in., and no heat-affected zone was visible in the silver – cadmium oxide contacts when viewed in section at a magnification of 1500 diameters.

Flash was expelled from the weld zone at high velocity. It eroded some sections of the tooling and produced buildup on others. As a result, the fixtures were checked and necessary maintenance performed at intervals of 10,000 assemblies.

Ultrasonic testing and metallographic examination were used in qualifying the welds. A group of 10 to 25 parts was used to set up the machine. During production, 3% of the welds were tear tested, 2% at the machine by the operator and 1% by the inspection department. Metallographic examination was used in troubleshooting, when results of routine tear tests were difficult to interpret.

The arc time was a half-cycle of 60-cycle alternating current (8 milliseconds). When loading and unloading were done manually, production rate was 400 welds (200 assemblies) per hour. When an automatic dial feed was used, production rate was 3600 welds (1800 assemblies) per hour.

In the previous production method, brazed assemblies were made by carbon-electrode resistance brazing at 100 joints (50 assemblies) per hour and induction brazing at 40 joints (20 assemblies) per hour.

The approximate cost for the basic percussion welding machine, including tooling for manual loading and unloading, was about $17,000. Cost for the completely automated machine was about $50,000.

Safety

Hazards to an operator or anyone near percussion welding equipment are as follows:

1 The noise level is high for welding large parts that have nib-type arc starters — for parts about ½ in. in diameter, it is similar to the noise from firing a 12-gage shotgun.
2 Weld flash and molten particles may be expelled from the joint at high velocity.
3 Highly toxic vapors are released in the welding of some metals — for example, silver – cadmium oxide.

In general, the severity of the hazards is approximately in proportion to the area of the weld, and is minimal for the welding of fine wires. Hazards from noise and weld flash can be minimized by shielding the weld area. Toxic vapors can be drawn off by an exhaust system. All three hazards can be minimized by enclosing the operation in a well-ventilated cabinet.

The operator should be protected from the welding voltage, particularly when high-voltage capacitors are used (see last paragraph in Example 179).

ARC WELDING OF METALS OTHER THAN LOW-CARBON STEEL

CONTENTS

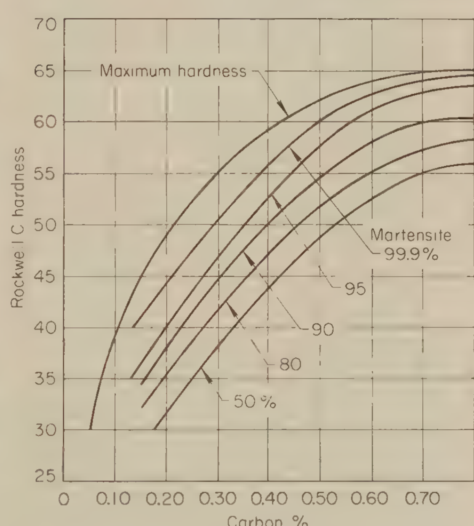
Arc Welding of Hardenable Carbon Steels

*By the ASM Committee on Welding of Hardenable Steel**

THE STEELS discussed in this article are the plain carbon steels that contain enough carbon to be hardenable during rapid cooling from welding temperatures. Hardening is caused by the formation of martensite. The greater the carbon content of the steel, the harder will be the martensite formed in that steel. Only very rapid cooling will produce 100% martensite and maximum attainable hardness. The effect of carbon content, and of the amount of martensite formed, on the hardness of carbon steel is shown in Fig. 1.

In most arc welding applications involving carbon steel, the cooling rate of the weld metal and the heat-affected zone is too low to develop the *maximum* hardness that steel of a specific carbon content can attain, because the hardenability of the steel is low. Nevertheless, an undesirable amount of hardening can occur, and the control of this hardening, together with the avoidance of cracking, constitutes the important difference between welding of low-carbon (mild) steel and hardenable carbon steel of medium or high carbon content.

In resistance welding, it is often possible to develop maximum or near-maximum hardness in a carbon steel, because a small volume of heated steel (the weld nugget) is cooled very rapidly by the large mass of cold metal that surrounds the nugget on all sides. Similar conditions can prevail during the arc welding of thick sections; a small bead of weld metal can be cooled so fast by the large volume of surrounding cold base metal that high hardness develops in the weld zone. Thus, the hardness of the weld zone of a carbon steel weldment depends on both the carbon content and the section thickness of the base metal.



Source of data: Curve for maximum hardness from Burns, Moore and Archer, Trans ASM, 26, 14, 1938; remainder of data from Hodge and Orehoski, Trans AIME, 167, 627, 1946

Fig. 1. Effect of carbon content on the hardness of carbon steel cooled rapidly to produce specific percentages of martensite, and (top line) the maximum hardness obtainable in severe water quenching of small specimens of carbon steel

Hardenability is the property that determines the depth and distribution of hardness induced by rapid cooling. Because the hardenability of carbon steels is low compared with that of alloy steels, carbon steels are generally less difficult to weld than are alloy steels of the same carbon content. In the welding of alloy steels, maximum hardness often is developed in the heat-affected base metal even when the cooling rate is low, because of the high hardenability of alloy steels (see the article on Arc Welding of Alloy Steels, page 200 in this volume).

As the carbon content of plain carbon steel is increased, the hardenability (as well as the hardness) increases. This is shown by the end-quench maximum

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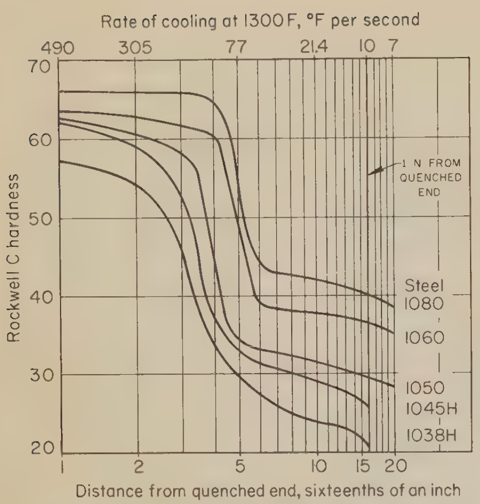
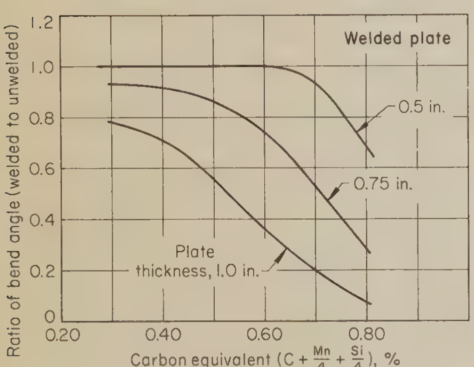
The examples presented in this article were contributed by members of other Metals Handbook welding committees.



Source of data: Steels 1038H and 1045H, 1970 SAE Handbook, p 19; steels 1050, 1060 and 1080, Metals Handbook, 8th edition, Volume 1, p 207

Fig. 2. Maximum hardenability of carbon steels, as determined by the standard end-quench test



Ratio (welded to unwelded) of bend angle for normalized steel plates. A high value of the ratio indicates high weldability. Derived from data on notch-bend tests by Stout and Doty ("Weldability of Steels", Welding Research Council, 1953).

Fig. 3. Effect of carbon equivalent and plate thickness on the weldability of carbon steels as indicated by notch-bend tests

hardenability curves for five plain carbon steels plotted in Fig. 2; comparing the five steels at 1 in. from the quenched end of the hardenability specimen (which corresponds to a cooling rate of 10 F per second at 1300 F), the hardness increases from Rockwell C 21 for 1038H steel to Rockwell C 40 for 1080 steel. Cooling rates of 10 F per second are not uncommon in arc welding, and if the hardness shown for a particular steel at the 1-in. position in Fig. 2 is unacceptable (or is associated with cracking), measures must be taken to avoid the development of this hardness, or to decrease it, as discussed later in this article.

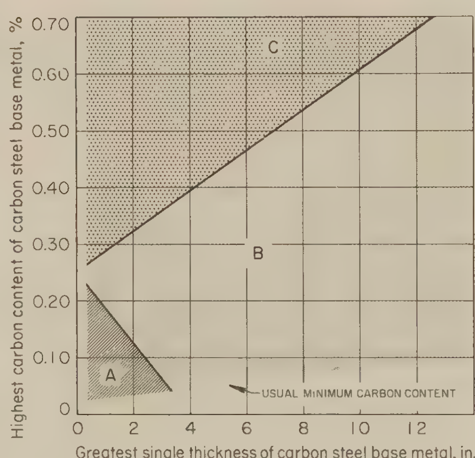
Classification of Carbon Steels

Specific carbon contents that separate low, medium and high-carbon steels are arbitrary.

Low-carbon steels, considered here as those containing less than 0.25% carbon, are generally easy to join by any arc welding process. The arc welding of these steels is discussed in detail in the first six articles in this volume (pages 1 to 147). Welds of acceptable quality can usually be produced without the need for preheating, postheating, or special welding techniques, provided the sections being welded are less than 1 in. thick and there is no severe joint restraint. Electrode selection is seldom critical for welding low-carbon steel.

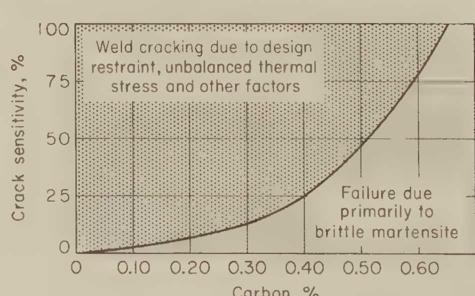
Medium-carbon steels, considered here as those containing 0.25 to 0.50% carbon, can also be satisfactorily welded by all of the arc welding processes, but because of the formation of greater amounts of martensite in the weld zone, and the higher hardness of the martensite, preheating or postheating, or both, are often necessary.

For joints and arc welding methods in which the weld zone is rapidly cooled, preheating is effective in minimizing hard, brittle martensitic areas. By postweld heating, it is possible to restore ductility in the heat-affected zones. Modifications in welding procedure — for example, the use of a larger V-groove or multiple passes — will also decrease the cooling rate and the probability of weld cracking. In multiple-pass welding, it is good practice to deposit the final weld bead in such a fashion that it is surrounded on both sides by weld metal from previous passes. By so doing, the heat-affected zones that resulted from the deposition of the previous-pass weld beads are tempered by the heat from the final-pass bead.



A—Neither preheating nor postweld stress relieving is usually required.
B—Preheating is usually required; postweld stress relieving is not usually required.
C—Both preheating and postweld stress relieving are usually required.

Fig. 4. Combined influence of base-metal thickness and carbon content on weldability, expressed in terms of the need for preheating and postweld stress relieving as defined in the list above (J. Heuschkel)



Summary of an investigation in a large fabricating plant to determine causes of cracking in carbon steel weldments. Brittle martensite was a minor cause of weld cracking in steels of lower carbon content but the major contributor for steels in the higher carbon range.

Fig. 5. Effect of carbon content on the cause of weld cracking in carbon steels

Selection of electrodes for arc welding becomes more critical as the carbon content of the steel increases. Steels with higher carbon content are more susceptible to cracking caused by hydrogen; therefore, low-hydrogen electrodes are ordinarily used in shielded metal-arc welding. As the carbon content of the steel being welded approaches 0.50%, the use of low-hydrogen conditions becomes mandatory.

High-carbon steels, with more than 0.50% carbon, are difficult to weld because of their susceptibility to weld cracking. The arc welding of these steels is more critical than is gas welding. Excessive hardness and brittleness are probable.

For best results in shielded metal-arc welding, the use of low-hydrogen electrodes is mandatory. Similarly, for other arc welding processes, low-hydrogen conditions are mandatory. Both preheating and postweld stress relieving or tempering are usually required. Austenitic stainless steel electrodes are sometimes used for welding high-carbon steel, to obtain greater notch toughness in the joint. However, the heat-affected zone may still be hard and brittle, and preheating and postweld stress relieving may be necessary.

Successful welding of high-carbon steel requires the development of specific welding procedures for each application. Composition, thickness and configuration of the component parts, and the service requirements, must be considered. For each application, the welding procedure should be qualified by tests before it is adopted.

Weldability

Weldability is a measure of the ability to make sound, strong welds. For a given joint, the chief factors influencing the making of good welds are steel composition, heat input, and rate of cooling. Heat input and rate of cooling are characteristics of the welding process and the technique used; they are also influenced by the dimensions of the sections being welded. For carbon steels, the carbon and manganese contents largely determine the extent and magnitude of hardening under given heating and cooling conditions.

The higher-carbon, higher-manganese grades of carbon steel can be welded satisfactorily if they are preheated and postheated. Sometimes peening of the hot weld bead is helpful, but many codes do not permit the use of peening, because it is difficult to control.

In the absence of procedures for controlling the rate of cooling and for eliminating high gradients of temperature and stress, cracks are likely to occur in both the weld metal and the base metal. In addition, the ductility and notch toughness of the base metal may be greatly reduced.

Carbon equivalent is sometimes used as a rough guide in the evaluation of weldability. However, the section size

being welded has an important influence on the combined effect of carbon and manganese contents on weldability, because of its relation to heat input and cooling rate. Figure 3 shows the effect of section thickness and carbon equivalent on weldability, as expressed in terms of notch-bend test results.

Several different equations for expressing carbon equivalent are in common use. The one shown as the horizontal legend of Fig. 3 (C + Mn/4 + Si/4), which considers only carbon, manganese and silicon, is appropriate for most carbon steels. Another well-known equation for expressing carbon equivalent that is sometimes used for carbon steel considers, in addition to manganese, residual (or higher) amounts of chromium and molybdenum — the two elements that are most likely to affect hardenability and weldability when present in small amounts. The equation is as follows:

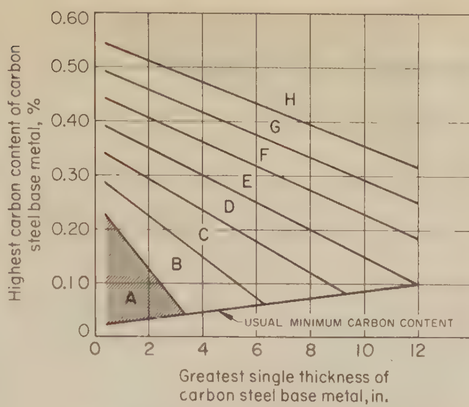
$$\text{Carbon equivalent} = \text{C} + \frac{\text{Mn}}{6} + \frac{\text{Cr}}{5} + \frac{\text{Mo}}{4}$$

This equation yields considerably lower carbon equivalents than the equation used in Fig. 3. For example, for a steel containing 0.35 C, 0.80 Mn, 0.20 Si, and only trace amounts of chromium and molybdenum, the carbon equivalent is 0.60% by the equation of Fig. 3 and 0.48% by the equation that neglects silicon but includes chromium and molybdenum.

Although a carbon equivalent is sometimes useful in planning welding procedures, its value is limited because only the chemical composition of the steel is considered. Section thickness and joint restraint are of equal, or greater, importance. Figure 4 relates carbon content and section thickness to weldability, expressed in terms of the need for preheating and postweld stress relieving. Combinations of carbon content and section thickness in the lower left portion of the chart (area A) are easily weldable. Combinations in area B usually require preheating, and those in area C usually require both preheating and postweld stress relieving. The use of low-hydrogen electrodes can offset, to some extent, the requirement for preheating, by shifting upward the lines that separate the three zones.

Weld Cracking

Susceptibility to weld cracking increases as the number of unfavorable welding conditions increases. For example, 1065 steel welded with an E7024 electrode (not classified as a low-hydrogen electrode), without preheat or postheat, performed satisfactorily when joint restraint was low and cycle loading of the weldment in service was limited. The heat-affected zone exhibited a region of martensite about 1/16 in. thick, but no cracking. However, when the section thickness was doubled, the thickness of the martensite zone increased, and cracking resulted. Changing to a low-hydrogen electrode (E7018) did not prevent cracking of the thicker section. The use of a 600 F preheat prevented cracking by retarding the rate of cooling and thereby reducing the amount of martensite formed.



Area	Range of preheating and interpass temperatures, F: Welding with high-hydrogen electrodes(a)	Welding with low-hydrogen electrodes
A	50 to 100	50 to 100
B	100 to 200	50 to 100
C	200 to 300	100 to 200
D	250 to 400	150 to 300
E	300 to 500	200 to 400
F	350 to 600	250 to 500
G	400 to 700	300 to 600
H	450 to 800	400 to 800

(a) In practice, it is usually considered mandatory to use low-hydrogen electrodes for welding steels containing 0.50% carbon or more.

Fig. 6. Effect of base-metal carbon content and thickness on preheating and interpass temperatures for shielded metal-arc welding of carbon steel (J. Heuschkel)

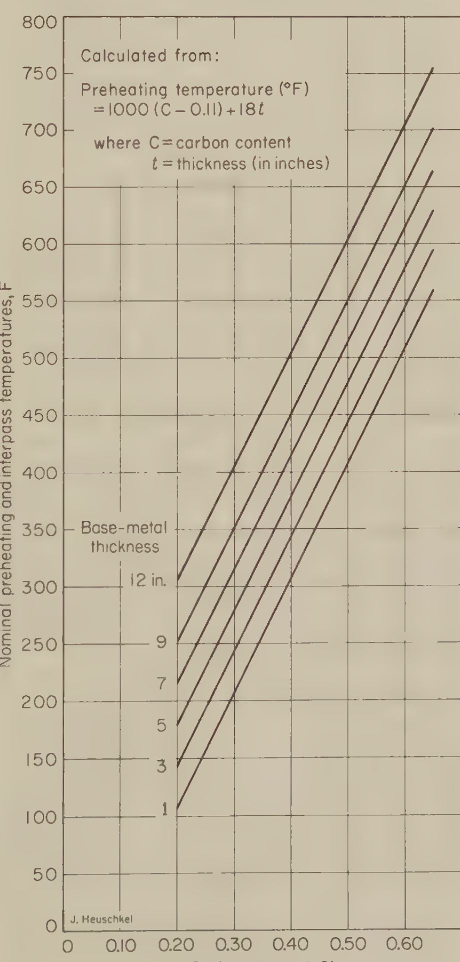


Fig. 7. Effect of base-metal carbon content on preheating and interpass temperatures for six section thicknesses of carbon steel welded by the shielded metal-arc process

Weld cracking is correlated with carbon content in Fig. 5, which summarizes a study made in one plant of a variety of welded components. Cracks occurring in weldments made of steels of lower carbon content were attributed chiefly to design restraint and unbalanced thermal stresses. In weldments made of steels of high carbon content, hardening (brittle martensite) was the major cause of weld cracking.

Underbead cracking can occur in any steel, but is most likely to occur in steels containing more than 0.20% carbon. High restraint, unbalanced thermal stresses, improper welding sequence in restrained designs, and inadequate penetration to the root of the joint are common causes of underbead cracking. However, the primary cause of underbead cracking is moisture — in the electrode covering (shielded metal-arc welding), in the flux (submerged-arc welding), on the base metal, or in the atmosphere. Moisture causes atomic hydrogen to form in the arc. Grease, oil and other hydrocarbons are also sources of hydrogen. The weld metal, because it is molten, will pick up more hydrogen than will the base metal, but both will absorb hydrogen at elevated temperatures. Because hydrogen also diffuses out at high temperatures, keeping the weldment at the preheat temperature or using a postweld heat treatment immediately after welding will help to prevent cracking. However, use of low-hydrogen electrodes in shielded metal-arc welding, or low-hydrogen conditions in other arc welding processes, will minimize the amount of hydrogen that contacts the weld.

Preheating and Interpass Temperature

Preheating an assembly for welding is intended primarily to prevent cracking in the weld or in the heat-affected zone. With preheating, the hardness in the heat-affected zone will usually be lower, because cooling rate is slower, and residual stress and distortion will be minimized. Many code-governed weldments have mandatory requirements, and specific conditions, for preheating.

The need for preheating of carbon steel is based not on carbon content alone, but rather on the combination of carbon, manganese, silicon and residual alloy contents along with various aspects of joint configuration — chiefly section thickness. Likewise, the selection of a preheating temperature is determined largely by this combination. Figures 6 and 7 relate the selection of preheating and interpass temperatures to carbon content and section thickness. The data and experience from which these graphs were developed were obtained with shielded metal-arc welding. Similar relations would apply to gas metal-arc and flux-cored arc welding. Less restrictive relations would sometimes be applicable for submerged-arc welding, which characteristically involves lower cooling rates for a given joint.

Welding at low ambient temperature (especially below room temperature) can cause cracking, and preheating to a safe-to-weld temperature is usually

the easiest and most effective preventive. If there is doubt concerning the composition of the steel being welded, preheating should be at a temperature conservatively on the high side. The use of low-hydrogen electrodes will frequently eliminate the need for preheating of thinner sections.

Bead size is also related to preheating. Small beads cool faster than large beads. Increasing the size of the bead by reducing travel speed, for example, increases heat input for a given length of weld, which results in a slower cooling rate, thus producing less martensite and lower hardness in the heat-affected zone. In some applications, the need for preheating has been eliminated by control of bead size.

Multiple-pass welding can sometimes reduce or eliminate the need for preheating. In certain applications where cracking has occurred when welding was done with a single pass and with no preheating, changing to multiple-pass welding has prevented cracking (without preheating). Under these conditions, the first pass serves as a preheat for the second pass, and the second pass as a preheat for the third. Each filler pass also provides some postheating effect for earlier passes.

Methods of Preheating. Ideally, a weldment is preheated in a furnace, but sometimes no furnace is available or the weldment is of such size or shape that furnace heating is not feasible. Under these conditions, preheating is usually done with gas torches, and temperature-sensitive crayons (or a surface pyrometer) are used for monitoring temperature.

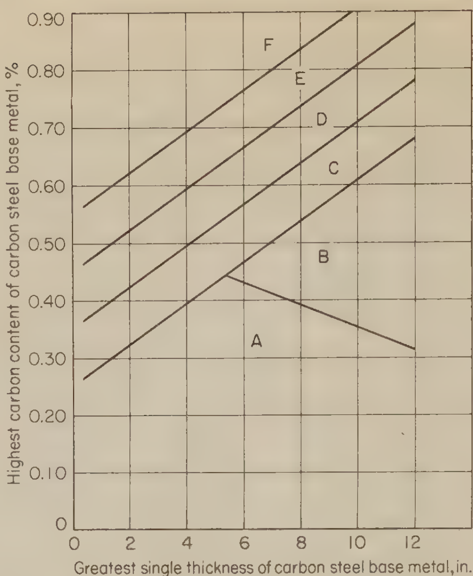
When preheating is done with torches, regardless of the temperature selected, the heat should be applied at one face of the joint and measured at the opposite face to ensure that the joint is heated through, or the preheating temperature should extend for a distance of 3 in. in each direction from the joint to be welded.

Interpass Temperature. In multiple-pass welding, if preheating is needed it is usually equally necessary to maintain a minimum interpass temperature equal to the minimum preheating temperature. However, if welding conditions are changed, such as a change in process or electrode, after deposition of the first bead, the interpass temperature should be adjusted to suit the new conditions. Suggested preheating and interpass temperatures, based on carbon content and thickness of the base metal, are given in Fig. 6 and 7.

In many automatic welding processes (especially in submerged-arc welding), enough heat is supplied to the joint so that additional heating between passes may not be required.

Postweld Stress Relieving

Stress relieving or tempering after welding of hardenable carbon steel is often desirable, and in some applications it is mandatory. Many codes define the conditions under which stress relieving is required, and the time and temperature of the stress-relieving cycle. The times and temperatures prescribed in these codes can be used for noncode applications of the same steels.



A—Postweld heating seldom is required.
B—Postweld heating is required only for dimensional stability, as when parts are to be finish machined after welding.
C—Postweld stress relief is highly desirable for repetitively loaded or shock-loaded structures and for restrained joints having a thickness greater than 1 in.
D—Postweld stress relief is required for all repetitively loaded or shock-loaded structures, for all restrained joints, and for all thicknesses over 2 in. It is also desirable for statically loaded structures.
E—Postweld stress relief is recommended for all applications. No intermediate cooldown should be permitted for restrained structures or for base metal having a thickness greater than 2 in.
F—Same as E, except hazards are greater.

Fig. 8. Effect of base-metal thickness and carbon content on requirements for postweld stress relieving or tempering of carbon steels (J. Heuschkel)

Although other variables, such as joint restraint, influence the need for postweld stress relieving, the principal factors are the same as for preheating — that is, base-metal thickness and carbon content. In Fig. 4, area C defines the combinations of base-metal thickness and carbon content for which postweld stress relieving is usually required. A more detailed chart for postweld stress relieving is presented in Fig. 8. The six areas into which Fig. 8 is divided take into account various conditions of welding and service that relate to the need for stress relieving, as explained below the graph.

The temperatures generally used for stress relieving of medium-carbon steels range from 1100 to 1200 F. The time at temperature is usually 1 hr per inch of maximum base-metal thickness, up to a maximum of 8 hr.

It is generally desirable to place the weldment in the stress-relieving furnace before it cools below the minimum preheat or interpass temperature, although this is not always feasible and is seldom considered mandatory for plain carbon steels. The heating and cooling of a weldment in a furnace during stress relieving must be at a gradual rate that will minimize the temperature gradient across the section thickness. A general formula for heating and cooling rates has not been found suitable for all shapes and materials. Section VIII of the ASME Boiler and Pressure Vessel Code defines the conditions under which postweld heat treatment must be applied for stress relieving of unfired pressure vessels.

Stress relief of weldments requires that the weldment be properly supported during the stress-relieving heat treatment, to prevent excessive distortion from relaxation of stresses.

Local reheating will soften hard zones, just as placing the entire weldment in a furnace will, but it may not reduce residual stresses. In order to stress relieve by localized reheating, the temperature gradient must be controlled and restriction of movement minimized. Local reheating can be dangerous if misapplied. A cycle of local heating and cooling can intensify residual stresses rather than relieve them.

Joint Preparation

Careful preparation of the weld joint is important. The joint edges can be sheared, machined, ground, chipped, gas cut or arc cut to the desired shape.

Cold working of the metal adjacent to a joint, either in preparing the joint or in cold forming after edge preparation, can cause cracks that can propagate and become large fractures. Gas cutting of high-carbon steels produces a heat-affected zone of hard, brittle metal, the hardness and depth of which increase with increasing carbon equivalent. The effects of gas cutting on medium-carbon steel, and the use of preheating and postheating to obtain an edge with the desired properties, are described on pages 284 to 287 in the article on Gas Cutting, in Volume 4 of this Handbook. Annealing or normalizing may be necessary following gas cutting, to restore the original structure of the steel.

Before welding, irregularities such as nicks, cracks and gouges that could act as stress raisers must be ground out, and grease, paint, surface scale, oxide, water and other foreign material must be removed. Because some carbon steels are sensitive to underbead cracking from hydrogen, water in any form — moisture in scale, humid atmosphere, rain, snow — should be removed, and a low-hydrogen electrode is recommended.

In the example that follows, cracking of weld metal was prevented by two methods of joint preparation. Because large, heavy-section pieces were being welded, preheating and postweld stress relief were not feasible, but cracking was avoided either by reducing joint restraint or by increasing the size and strength of weld metal.

Example 181. Two Methods of Joint Preparation That Prevented Weld Cracking Due to Joint Restraint and Loss of Ductility (Fig. 9)

Weld cracking occurred when heavy 1045 steel channel sections 10 to 20 ft long (see Fig. 9) were joined back-to-back with single-pass welds made by the shielded metal-arc process, using low-carbon steel filler metal (E6010). The cracking was ascribed to: (*a*) the restraint of the heavy sections (36.5 lb per foot) on the welds during cooling and contraction; (*b*) loss of weld ductility due to carbon enrichment of the weld metal by the 1045 steel base metal; (*c*) rapid chilling of the weld metal by the large mass of surrounding base metal; and (*d*) small cross-sectional area of the bead.

In an attempt to prevent cracking, low-hydrogen electrodes, including E7016 and the higher-strength E12018, and 35Cr-15Ni electrodes were tried, but results were little better than those obtained with E6010. Cracking always occurred through the centerline of the weld, which indicated lack of strength or ductility, or both, rather than hydrogen embrittlement.

Next, a revision in joint preparation for welding was made. Two methods were equally effective in preventing weld cracking. In one (method A in Fig. 9), the channel sections were separated by copper wires, 1/16 in. in diameter and 9 in. long, which were placed perpendicular to the channel flanges at 2-ft intervals. To hold the wires and the channels in proper position for welding, strong tack welds were placed near each wire. Both sides of the joint were shielded metal-arc welded with E6010 or E6011 electrodes, working from the center toward the ends. Because of the length of the channels, welding was alternated from side to side every few feet, to avoid cambering. The weld beads were deposited in a single pass, with deep penetration of the base metal. As the welds cooled, the soft copper yielded sufficiently to reduce shrinkage stress.

The other method used to avoid weld cracking (shown as method B in Fig. 9) involved the use of intermittent V-groove welds 4 in. long, spaced on 8-in. centers; joint edges were chamfered to form a 60° V-groove of 1/4-in. minimum depth. After the channels had been placed back-to-back, clamped and tack welded, they were shielded metal-arc welded with low-carbon steel electrodes of the E60*xx* or E70*xx* class. The welds were single-pass welds, deposited from the center toward the ends. Each 4-in. weld was allowed to cool before the next one was begun. To avoid cambering, welding was alternated from side to side after every two welds. Because the V-grooves increased the cross-sectional area of the welds, weld strength and ductility were increased sufficiently to enable the weld to withstand stresses developed by joint restraint and to prevent cracking. Although some of the ductility gained by depositing a greater amount of weld metal undoubtedly resulted from a lesser amount of carbon pickup from the base metal, it was mostly because a greater amount of hot metal was available for elongation or compression.

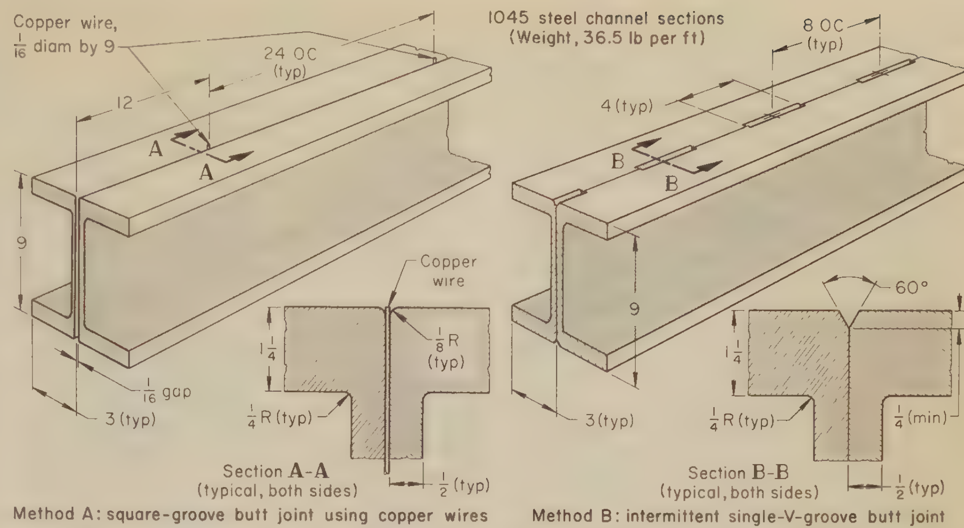


Fig. 9. Two methods of joint preparation for shielded metal-arc welding of heavy channel sections back-to-back, to avoid weld cracking due to joint restraint and insufficient weld ductility (Example 181)

Shielded Metal-Arc Welding

Shielded metal-arc welding is used extensively for joining hardenable carbon steel. In general, the equipment, techniques and difficulties discussed in the article on Shielded Metal-Arc Welding, pages 1 to 23, apply to the welding of hardenable carbon steel.

The use of low-hydrogen electrodes is important in welding hardenable carbon steel. Electrodes with flux coverings that contain cellulose will release hydrogen, which, when absorbed in the hardened zone of a weld, can cause underbead cracks, especially in steel with a high carbon equivalent. Cracking is minimized by the use of low-hydrogen electrodes, by proper storing and drying procedures, by minimizing carbon pickup from the base metal, by selection of electrodes and welding techniques that minimize melting of the base metal, by preheating, and by maintaining an appropriate interpass temperature (see Fig. 6 and 7).

Transferring the weldment to a furnace for postweld stress relieving while it is at or above the interpass temperature is desirable for steels of higher carbon content or higher hardenability.

Large tonnages of hardenable carbon steels are used for applications where weld integrity is imperative, and various welding codes and standards have been developed for these applications. The heating requirements set forth in these codes can be used for applications that are not governed by codes.

Electrodes. The type and size of electrode selected depend on the composition of the steel, its thickness, joint preparation, welding position, and available welding current. Not all of the electrodes covered by AWS specifications A5.1-69 and A5.5-69, which apply to low-carbon steel and low-alloy steel covered electrodes, respectively, are suited for welding hardenable carbon steel. Although hardenable carbon steels are sometimes welded with cellulose-type (high-hydrogen) covered electrodes such as E6010, low-hydrogen electrodes are generally preferred. Among the electrodes most often used are E7015, E7016, E7018, E8016-C1, E8016-C3, E8018-C1, E8018-C3, E10016-D2 and E10018-D2. Of this group, E7018 electrodes are the ones most used. Ranges of welding current for use with various sizes of the above electrodes are given in Table 1.

E7015 and E7016 electrodes are low-hydrogen low-carbon steel electrodes. E7015 electrodes are used with reverse-polarity direct current, and E7016 electrodes are used with alternating current and reverse-polarity direct current. These electrodes are applicable to the welding of hardenable carbon steels that are subject to underbead cracking due to the presence of hydrogen; they can be used without preheating of the metal to be welded or with preheating to a lower temperature than would be necessary with other than low-hydrogen electrodes. However, if E7015 or E7016 electrodes are used without preheating, the notch toughness of the weld will generally be lower than if preheating is employed. The E7015 or E7016 electrodes are also used in the welding of high-sulfur steels; electrodes that are not of the low-hydrogen type are likely to deposit porous weld metal.

With E7015 and E7016 electrodes, the arc, which is moderately penetrating, should be kept as short as possible; the slag is moderately difficult to remove; and the bead shape is slightly convex.

E7018 electrodes are low-hydrogen, iron-powder, low-carbon steel electrodes for use with alternating current and reverse-polarity direct current. These electrodes deposit essentially the same composition of weld metal as E7016 electrodes. The electrode covering contains essentially the same low-hydrogen materials as E7016, but the 25 to 45% iron powder gives E7018 electrodes a higher deposition rate. With E7018 electrodes, the arc, which is moderately penetrating, should be kept as short as possible, the slag is moderately difficult to remove, and the bead shape is slightly convex.

E7018 electrodes can be used in any welding position, and thus are preferred for a wide range of applications.

Low-Alloy Steel Electrodes. With suitable precautions, the low-alloy steel electrodes discussed below can be used for welding hardenable carbon steel, as well as for welding the low-alloy steels for which they were originally developed. They have higher strength than the E70*xx* electrodes.

E8016-C1 and E8018-C1 electrodes are low-alloy, low-hydrogen electrodes for use with alternating current or reverse-polarity direct current. Weld deposits from these electrodes contain about 2.5% nickel. The electrodes are widely used when low-temperature notch toughness is required.

In joints welded using preheat and interpass temperatures of 200 to 225 F and stress

Table 1. Ranges of Welding Current for Various Sizes of Electrodes Used in Shielded Metal-Arc Welding of Hardenable Carbon Steels(a)

Electrode diameter, in.	Current, amp, for electrode of class: E7015, E7016	E7018	E8016-C1, E8018-C1	E8016-C3	E8018-C3	E10016-D2, E10018-D2
3/32	65 to 110	70 to 100	80 to 120	70 to 90	70 to 95	60 to 100
1/8	100 to 150	115 to 165	100 to 150	100 to 130	110 to 140	80 to 120
5/32	140 to 200	150 to 220	150 to 185	130 to 180	130 to 200	140 to 190
3/16(b)	180 to 255	200 to 275	200 to 250	165 to 230	165 to 290	180 to 250
7/32(b)	240 to 320	260 to 340	240 to 325	270 to 300	280 to 315	....
1/4(b)	300 to 390	315 to 400	300 to 425	290 to 330	320 to 400	300 to 400
5/16(b)	375 to 475	375 to 470	....	....	....	....

(a) Lower sides of current ranges are used for vertical or overhead welding; higher sides of current ranges, for welding in the flat position. (b) Not used in all welding positions.

relief at 1150 F, weld metal is required to have the following minimum properties:

Tensile strength	80,000 psi
Yield strength, 0.2% offset	67,000 psi
Elongation in 2 in.	19%

The required Charpy V-notch impact value (at −75 F) for these joints is 20 ft-lb.

The operating characteristics of these electrodes are similar to those of E7016 electrodes.

E8016-C3 and E8018-C3. E8016-C3 electrodes are low-alloy, low-hydrogen electrodes for use with alternating current and reverse-polarity direct current. The weld deposit contains about 1% nickel. When these electrodes are supplied as iron-powder types, they are designated E8018-C3.

In joints welded and tested in conformance with AWS A5.5-69, using preheat and interpass temperatures of 200 to 250 F and no stress relief, the weld metal is required to have the following minimum properties:

Tensile strength	80,000 psi
Yield strength, 0.2% offset	68-80,000 psi
Elongation in 2 in.	24%

The required Charpy V-notch impact value (at −40 F) for these joints is 20 ft-lb.

The operating characteristics of these electrodes are similar to those of E7016 and E7018 electrodes, respectively.

E10016-D2 and E10018-D2 electrodes are low-alloy, low-hydrogen electrodes for use with alternating current and reverse-polarity direct current. The weld deposit contains about 1.75% manganese and 0.35% molybdenum. The electrodes were designed for welding high-strength steels of high hardenability, but they have been used for welding carbon steels containing 0.30% carbon or more, when high strength of the weld deposit is required.

In joints welded using preheat and interpass temperatures of 200 to 225 F and stress relief at 1150 F, weld metal is required to have the following minimum properties:

Tensile strength	100,000 psi
Yield strength, 0.2% offset	87,000 psi
Elongation in 2 in.	16%

The required Charpy V-notch impact value (at −60 F) for these joints is 20 ft-lb.

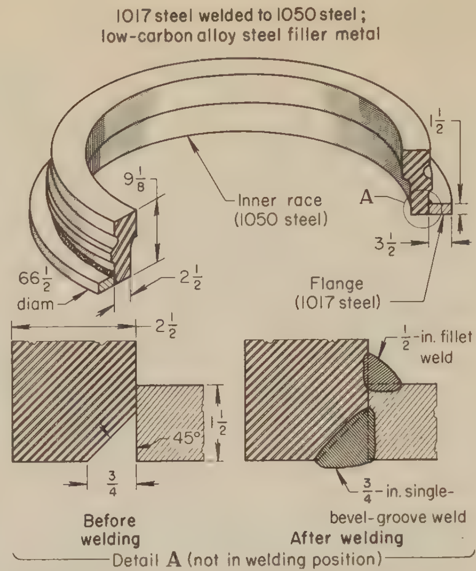
Control of Moisture Content of Electrodes. Because hardenable carbon steels are susceptible to underbead cracking when welded with an arc that contains hydrogen, the moisture content of electrode coverings should be kept at a very low level, which can be done by careful storage and use of electrodes. For information on the care and reconditioning of low-hydrogen electrodes, see "Low-Hydrogen Coverings" on page 7 in the article on Shielded Metal-Arc Welding.

Flux-Cored Arc Welding

For the most part, the process, equipment and techniques discussed in the article on Flux-Cored Arc Welding, pages 24 to 45, apply to the welding of hardenable carbon steel (Example 20 in that article deals with welding of 1045 to 1055 steel).

The procedures for preheating and postheating presented earlier in this article, although generally oriented toward shielded metal-arc welding, apply to a large extent to flux-cored arc welding. However, in welding steels of undetermined weldability, heating procedures must be established with caution. The process should be qualified for the specific application.

Although flux-cored electrode wires are available for welding a wide variety of steels, only low-carbon steel electrode wires have thus far (1971) been covered by specifications. These specifications are discussed in the Appendix to "Flux-Cored Arc Welding", pages 41 to 45 in this volume. Experience and information on the use of the standard electrodes in welding hardenable carbon steels are limited. In the following three examples, electrodes of the E70T-1 classification were used for three different hardenable carbon steel weldments.



Automatic Flux-Cored Arc Welding(a)

Joint types	Corner and butt
Weld types	Fillet and single-bevel groove
Power supply	750-amp rectifier(b)
Electrode holder	Mechanically held, air cooled
Electrode	7/64-in.-diam flux-cored wire(c)
Shielding gas	Carbon dioxide, at 40 cfh
Welding position	Flat
Number of passes:	
Single-bevel-groove weld	Three
Fillet weld	Two
Current (dcrp) and voltage:	
Root pass	550 amp; 28 to 30 v
Filler pass	550 to 600 amp; 32 to 34 v
Welding speed:	
Root pass	25 ipm
Filler pass	13 ipm
Preheat temperature	600 F
Interpass temperature (minimum)	600 F
Postheat	None(d)

(a) Equipment included: an automatic, constant-speed wire feeder; a variable-speed rotating positioner with a universal clamping fixture; a ram-type manipulator for supporting the welding head; and two natural-gas preheating torches on pedestals. (b) Constant-voltage. (c) Composition, 0.06 C, 1.60 Mn, 0.40 Si, 2.30 Ni, 0.40 Mo. (d) Air cooled to room temperature; later the race area only was induction hardened.

Fig. 10. Ball-bearing inner-race assembly that was joined with high-quality welds by the automatic flux-cored arc process (Example 185)

Examples 182, 183 and 184. Flux-Cored Arc Welding vs Shielded Metal-Arc Welding for Three Different Applications (Table 2)

For each of the three applications listed in Table 2, shielded metal-arc welding had been used, and the process was changed to flux-cored arc welding with auxiliary gas shielding, at a substantial saving in welding time, generally from 35 to 50%. Continuous electrode feed, higher deposition rate, and higher travel speed with flux-cored arc welding were mainly responsible for the decreased welding time. No preheating nor postheating was required in these applications.

Details about the base metal, the type of weld, and welding conditions for flux-cored arc welding in the three applications are presented in Table 2.

The example that follows describes an application in which automatic flux-cored arc welding was used to produce welds suitable for service under severe loading and extremes of temperature.

Example 185. Welding Bearing-Race Assemblies by the Automatic Flux-Cored Arc Process (Fig. 10)

Ball-bearing inner-race assemblies 2 to 10 ft in diameter, each consisting of a 1050 steel inner race and a 1017 steel flange, were joined by two circumferential welds, using the automatic flux-cored arc process with auxiliary gas shielding. As indicated in Fig. 10, which shows a typical bearing race, the welds were a ½-in. fillet weld and a ¾-in. single-bevel-groove weld.

Because the bearings were the main supports for mobile cranes and shovels, and were subjected to high loads and extreme weather conditions in service, sound welds with good mechanical properties were essential. The welds were specified to have no underbead cracks or other defects visible under dye-penetrant inspection. With the use of the welding conditions listed in the table with Fig. 10, crack-free welds with no evidence of slag inclusions or porosity were obtained. The weld metal had the following typical tensile properties:

Tensile strength	115,000 psi
Yield strength	102,700 psi
Elongation in 2 in.	20%
Reduction of area	42%

Although all processing conditions contributed to weld soundness, the most important were the use of preheating, the selection of a suitable low-carbon alloy steel electrode wire (see footnote in table with Fig. 10), and the close control that is characteristic of automatic welding.

Submerged-Arc Welding

Submerged-arc welding is used both as a fully automatic and as a semiautomatic process for joining and for surfacing of hardenable carbon steels. The article on Submerged-Arc Welding, which begins on page 46 in this volume, discusses in detail the equipment, electrodes, fluxes, and procedures. Although that article primarily concerns low-carbon steels, most of the information in it is pertinent to the welding of carbon steels with higher carbon content (hardenable grades).

Procedures for preheating and postheating suggested in the earlier part of this article were oriented toward shielded metal-arc welding and do not necessarily apply to the same degree to submerged-arc welding. Preheating and postheating are less likely to be required for submerged-arc welding than for shielded metal-arc welding, for two reasons: (*a*) because of the high heat input and high deposition rate of submerged-arc welding, a larger area is heated, and consequently, the cooling rate is lower and the probability of hardening is lessened; and (*b*) the flux blanket helps to retard cooling. However, in many applications, preheating and postheating are needed in submerged-arc welding of hardenable carbon steels. Each application must be evaluated separately.

The submerged-arc process is ordinarily capable of depositing low-hydrogen weld metal, provided the flux is properly dried and other precautions, including keeping the area surrounding and including the joint free of moisture, oil, grease, paint, scale, or other material that could be a source of hydrogen, are observed. The flux, which

may be hygroscopic, must be kept dry. Proper storage and handling are important. A widely followed practice for maintaining low-hydrogen conditions is to keep the flux in an oven at about 250 F for several hours before it is needed.

The use of preheat, controlled interpass temperature, and postweld stress relieving in joining low-carbon steel arms to a medium-carbon steel shaft is illustrated by the following example.

Example 186. Submerged-Arc Welding of 1015 Steel Arms to a 1038 Steel Shaft (Fig. 11)

The rotor shaft for a motor consisted of four longitudinal arms of 1015 steel joined to a premachined shaft of 1038 steel by two-pass submerged-arc welds.

The arms were beveled by either machining or gas cutting, and were shot blast cleaned before welding. The arms were aligned on the shaft by means of two retaining rings, and the entire assembly was preheated to 400 to 500 F before any welding was done. After preheating, one side of each arm was tack welded to the shaft, as shown in section A-A in Fig. 11, by shielded metal-arc welding with E7016 low-hydrogen electrodes. The shaft was then placed on the turning rolls of a positioner table, and the four arms were checked for alignment. Next, the tack welds were cleaned of slag, and the first passes by submerged-arc welding were made (see position 1 in section B-B in Fig. 11). First-pass weld beads were deposited on side 1 of each of the four arms (the side that had not been tack welded); then the shaft was turned end-for-end, and first-pass beads were deposited on side 2.

With the completion of all first passes, the welding electrode and shaft were repositioned for making the second passes (see position 2 in section B-B in Fig. 11). Second passes were completed on one side of each arm. At this point, the assembly was checked for alignment, so that any distortion could be corrected by changing the sequence of the remaining weld passes. The shaft was then turned end-for-end, and the second passes were made on the other side of the joints.

The placement of weld beads was specified to ensure a smooth transition from the arm to the shaft. The weld surface remained as-deposited, receiving no further finishing except for cleaning and slag removal. (Subsequently, attachments were made to the arms by shielded metal-arc welding with low-hydrogen electrodes.)

During the entire sequence of welding operations, the interpass temperature was held at a minimum of 400 F, and after completion of welding, the assembly was stress relieved at 1175 F for 1 hr per inch of maximum section thickness. The heating rate was 150 F per hour, and the controlled cooling rate was 150 F per hour to 300 F. Additional details of welding conditions are presented in the table with Fig. 11.

Previously, this rotor shaft had been machined from a fluted open-die forging at a cost that was competitive with the cost of the welded assembly. However, because the rotor shafts were produced in a variety of shapes, and with major shaft diameters ranging from 4½ to 10 in., lead times for the forgings gave rise to inventory and handling charges that were considered unnecessary. The change to a weldment eliminated these costs, because the lead time for the components for the welded assembly was less than for the forging. Shafting stock and plate for the arms were readily available, and the arms were gas cut from plate as needed.

Gas Metal-Arc Welding

Gas metal-arc welding is widely used for joining hardenable carbon steels. The article on Gas Metal-Arc Welding, which begins on page 78 in this volume, discusses in detail the advantages, disadvantages, applicability, principles, equipment, shielding gases, design, costs, and safety problems associated with this process. Although the above article is concerned primarily with the welding of low-carbon steel, much of the information is pertinent to the welding of hardenable carbon steels.

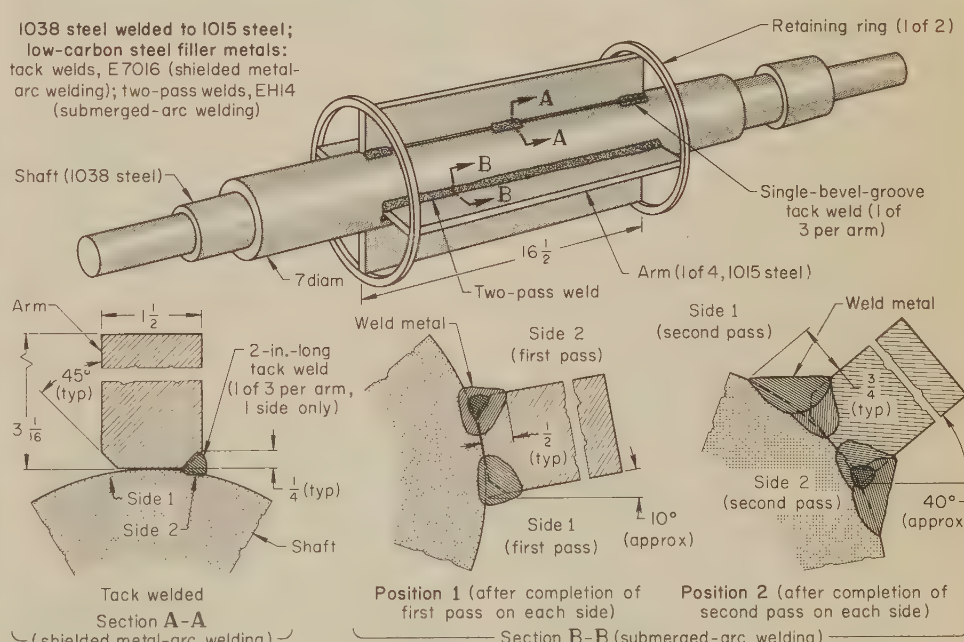
The preheating and postheating practices described earlier in this article for shielded metal-arc welding are frequently applicable to gas metal-arc welding. However, they are not always the same. For example, the depth of penetration can influence preheating practice, and this is likely to differ between the two processes. Furthermore, there may be a difference in requirements for preheating among the different techniques for the gas metal-arc process. In some applications, the need for preheating is eliminated by using argon instead of carbon dioxide as a shielding gas, because of the difference in penetration patterns obtained with the two gases. The mode of metal transfer can also affect the need for preheating — the spray arc penetrates considerably deeper than the short-circuiting arc. Because of the many variables with gas metal-arc welding, it is more important to qualify the procedure for a given application than it is for other arc welding processes.

Because a shielding gas is used instead of a flux, the possibility of introducing hydrogen into the weld metal is minimal, but the usual precautions, including keeping the weld joint free of moisture, oil, grease, paint, scale, or other material that could adversely affect weld quality, should be observed to ensure sound welds. The electrode wire is sometimes a source of hydrogen, particularly if the surface is poor. Laps

Table 2. Operating Conditions for Three Applications of Automatic Flux-Cored Arc Welding of Hardenable Carbon Steels (Examples 182, 183 and 184)

Item	Example 182 (House-trailer axle)	Example 183 (Punch-press gear)	Example 184 (Sinter-pot flange)
Steel welded	1045	1020 and 1045	ASTM A285
Thickness	3/16 to 1/4 in.	...	2 in.
Joint type	Butt	T-joint	Edge
Weld type	...	1/2-in. fillet	(a)
Electrode wire	3/32-in.-diam E70T-1	3/32-in.-diam E70T-1	3/32-in.-diam E70T-1
Shielding-gas (CO_2) flow rate	...	45 cfh	55 cfh
Welding current (dcrp)	300 to 400 amp	600 amp	450 amp
Arc voltage	25 v	32 v	28 to 30 v
Power supply(b)	500 amp	750 amp	500 amp
Travel speed	50 ipm	10 ipm	18 to 24 ipm

(a) Single-bevel-groove weld, 45° by 1 9/32 in. deep, inside; 3/4-in. flat fillet, outside. (b) Constant-voltage motor-generator.

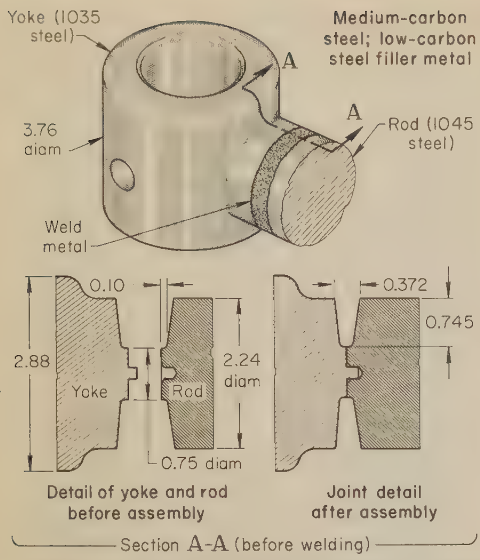


Conditions for Submerged-Arc Welding

Joint type	T
Joint preparation	Machining or gas cutting
Weld type, each side	Single-bevel groove
Electrode wire	5/32-in.-diam EH14(a)
Flux	F72
Welding position	Flat
Voltage	28 to 29 v
Current	540 amp, ac
Number of passes per side	Two
Welding speed, first pass	10 ipm
Welding speed, second pass	7 ipm
Preheat (before tack welding)	400 to 500 F
Interpass temperature (min)	400 F
Postheat	1175 F(b)

(a) Automatic feed. (b) For 1 hr per inch of maximum section thickness. Weldment was heated to 1175 F (and later cooled to 300 F) at 150 F per hour.

Fig. 11. Rotor-shaft assembly in retaining ring for submerged-arc welding, and details of joint design and weld-pass sequence that, together with preheating, maintenance of interpass temperature, and postweld stress relieving, minimized stress concentration (Example 186)



Automatic Gas Metal-Arc Welding

Power supply	300-amp rectifier, with controlled slope, voltage and inductance
Electrode wire	0.045-in.-diam low-carbon steel
Current	Reverse-polarity direct
Arc time	2.56 min
Shielding gas	75% A – 25% CO_2, at 28 cfh
Wire-feed rate	295 ipm
Preheat and postheat	None
Electrode consumption per weld	755 in.
Floor-to-floor time	3.43 min

Fig. 12. Yoke-and-rod assembly, and details of the deep circumferential joint welded by the automatic gas metal-arc process (Example 187)

or folds are likely to contain drawing lubricants.

Welding-grade argon is generally low in hydrogen. A minimum dew-point temperature of −60 F should be specified and certified by the vendor. Sometimes gas suppliers fail to drain and dry cylinders before refilling; this results in dew-point temperatures of −10 to −30 F, which are likely to cause cracking. The moisture content of welding-grade carbon dioxide used for gas metal-arc welding is usually at a dew point of −40 F or less.

An application for gas metal-arc welding of hardenable carbon steel is described in Example 78 in the article on Gas Metal-Arc Welding, and an application where the process was used for surfacing a hardenable carbon steel is described in Example 156 in the article on Hard Facing by Arc Welding.

Automatic Welding. In the three examples that follow, automatic gas metal-arc welding was used because of higher production rate and better quality of welds, and because less operator skill was needed.

Example 187. Automatic Circumferential Welding of a Yoke to a Rod Section (Fig. 12)

The steel yoke-and-rod assembly shown in Fig. 12 required a circumferential weld about ¾ in. deep, with a maximum width of about ⅜ in. at the top of the weld joint. The nature and magnitude of service loading required that the weld begin as close as possible to the center, or core, of the rod, which accounted for the design of the joint (see section A-A in Fig. 12).

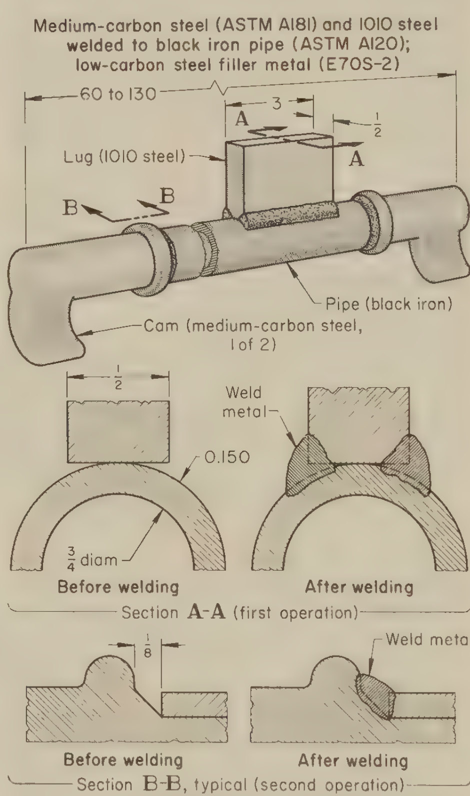
The automatic gas metal-arc process was selected for this application, on the basis of production rate and the ability of automatic welding to produce a narrow weld bead without overfill, so that little subsequent machining would be required. Total investment for the automatic equipment was less than $8000.

Details of the welding operation are given in the table that accompanies Fig. 12. The 1045 steel rod was welded in the cold finished, ground and polished condition. Despite the relatively thick sections (approximately 2¼ in.) and the fact that 1035 and 1045 steels are hardenable, no excessive hardness was obtained in the heat-affected zones. This was attributed to the relatively large amount of weld metal deposited and the use of multiple-pass welding, which functioned with about the same effect as preheating and postheating.

Example 188. Use of Automatic Gas Metal-Arc Welding for Joining Four-Component Door-Lock Assemblies (Fig. 13)

The weldment shown in Fig. 13 — a lock rod for a cargo-trailer door — consisted of two cams forged from medium-carbon steel (ASTM A181, 0.35% max carbon), a rectangular 1010 steel lug, and a length of standard ¾-in. black iron pipe (ASTM A120). Fully automatic gas metal-arc welding was selected for joining these components, for three reasons:

1 The welds were sounder and had better appearance than those made with semiautomatic welding.
2 Almost no distortion occurred when the lug was welded to the pipe.

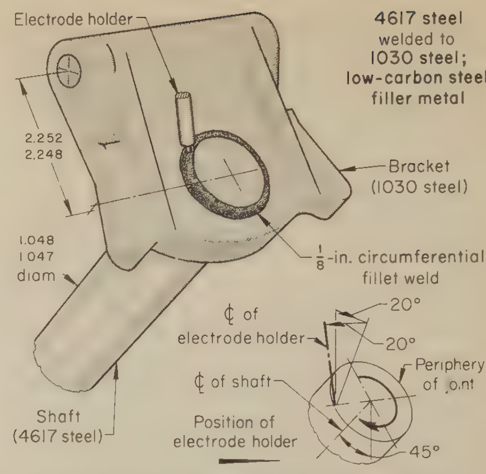


Automatic Gas Metal-Arc Welding

Power supply	Two 200-amp rectifiers(a)
Electrode wire	0.035-in.-diam E70S-2
Electrode holders	Air cooled, machine held
Wire feed	Automatic, constant feed
Current	170 amp, dcrp
Voltage	20 v
Arc type	Short circuiting
Shielding gas	Carbon dioxide, at 20 cfh
Preheat and postheat	None
Welding time, first operation(b)	12 sec
Welding time, second operation(c)	13 sec

(a) Constant-voltage type, with variable slope control. (b) Welds on both sides of lug were deposited simultaneously. (c) Both cams were welded to pipe simultaneously.

Fig. 13. Cargo-trailer door-lock assembly that was joined in two operations by automatic gas metal-arc welding (Example 188)



Semiautomatic Gas Metal-Arc Welding

Joint type	Corner, circumferential
Weld type	Fillet
Power supply	250-amp rectifier
Electrode wire	0.035-in.-diam, copper-coated low-carbon steel
Electrode holder	Mechanically held, air cooled
Current	225 amp, dcsp
Voltage	25 v
Shielding gas	Carbon dioxide, at 5 to 10 psi
Number of passes	One
Wire-feed rate	435 ipm
Welding time, floor-to-floor:	
Original method	1.734 hr per 100 pieces
Improved method	1.470 hr per 100 pieces
Preheat and postheat	None
Rejection rate	Less than 0.1%

Fig. 14. Bracket assembly for which semiautomatic gas metal-arc welding was fully automated to increase production (Example 189)

3 To meet production demand, at least three welders would have been required if semiautomatic welding had been used, whereas only one operator was required for the fully automatic setup.

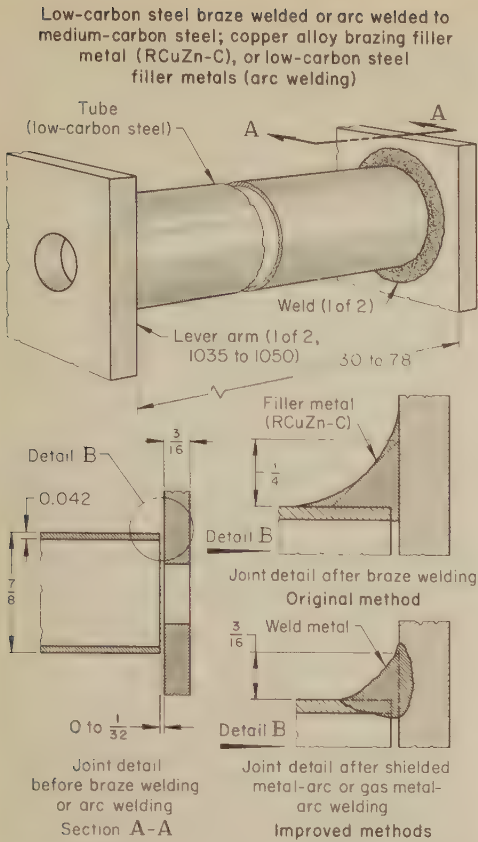
Welding was done in two operations. In the first operation, the rectangular lug was positioned on the pipe and welded to the pipe by means of fillet welds deposited on the two sides of the lug (see section A-A in Fig. 13). For this operation, the pipe and the lug were loaded into a fixturing mechanism, and the two welds were deposited simultaneously.

Welding time was 12 sec, and the production rate, including handling time, was 60 weldments per hour.

In the second operation, the pipe-and-lug weldment, with a cam placed at each end of the pipe, was loaded into the fixturing mechanism (adapted for circumferential welding), the cams were positioned in accurate dimensional relationship with the lug and automatically tack welded, and the assembly was rotated 180° before the initiation of circumferential welding.

Welding the two cams simultaneously (see typical joint detail in section B-B in Fig. 13) required that the assembly be rotated 360° plus a slight overlap. The assembly was then returned to the starting position and was unclamped and unloaded manually. Welding time was 13 sec, and production rate, including handling, was 40 weldments per hour.

Both welding operations were done in a special fixturing device designed to accommodate various types of cams, pipe lengths, and lug positions required to make both right-hand and left-hand assemblies ranging from 60 to 130 in. in over-all length. A full production quantity of parts was first-operation welded (lug to pipe) before the machine was adjusted for the second operation (pipe to cams). Longitudinal speed for the fillet welds was controlled by an air-hydraulic cylinder, and speed for the circumferential welds was controlled by an electronic variable-speed drive. Welding conditions are given in the table that accompanies Fig. 13.



Item	Braze welding(a)	Shielded metal-arc welding(b)	Gas metal-arc welding
Cost per Assembly			
Welding materials	$0.085	$0.014	$0.012
Direct labor	0.105	0.135	0.045
Total	$0.190	$0.149	$0.057

Conditions for Gas Metal-Arc Welding

Power supply	300-amp transformer-rectifier(c)
Electrode wire	0.035-in.-diam low-carbon steel
Electrode holder	Hand held; 150 amp(d)
Wire feed	Push type, continuously variable
Current	75 amp, dcsp
Voltage	25 v
Shielding gas	Carbon dioxide, at 22 psi (cylinders)
Number of passes	One
Wire-feed rate	255 ipm

(a) With an oxyacetylene torch set for a slightly oxidizing flame. Filler metal was RCuZn-C (low-fuming bronze); flux was a liquid proprietary mixture introduced into the flame by a fluxer. (b) With ⅛-in. E6012 electrodes 14 in. long, and direct current from a 300-amp transformer-rectifier. (c) Constant-voltage type, with slope control. (d) Light-duty type.

Fig. 15. Torque-tube assembly for which gas metal-arc welding was the least costly of three joining processes used (Example 190)

Example 189. Change From Semiautomatic to Automatic Operation for Faster Welding With Decreased Welder Skill (Fig. 14)

Increased production demand prompted a change from semiautomatic to automatic gas metal-arc welding for joining the components of the bracket assembly shown in Fig. 14 — a machined 4617 steel shaft and a forged 1030 steel bracket. The change resulted in an increased production rate, and a decrease in welding cost from $4.43 to $3.35 per hundred assemblies. Also, the automatic operation was satisfactorily performed by a less highly skilled operator, and the welded assemblies were more uniform and had a better appearance.

For automatic welding, the press-fitted assembly was held at a 45° angle while being rotated at constant speed. The fixture used was specially designed, and incorporated an air-operated device for positioning and retracting the electrode holder (position of the holder during welding is shown at lower right in Fig. 14). Except for manual loading and unloading, the cycle was fully automatic. Welding conditions are given in the table that accompanies Fig. 14. Weld quality was judged visually.

Gas Metal-Arc Welding vs Other Welding Processes. In the two examples that follow, improvement in weld quality and decreased manufacturing cost resulted from changing to semiautomatic gas metal-arc welding.

Example 190. Change From Braze Welding to Shielded Metal-Arc Welding and Then to Gas Metal-Arc Welding, To Reduce Welding Costs (Fig. 15)

A torque-tube assembly that coordinated the operation of parallel mechanisms of a folding bed consisted of two medium-carbon steel (the grade varied from 1035 to 1050) lever arms, 3⁄16 in. thick, and a 0.042-in.-wall low-carbon steel tube 30 to 78 in. long. The lever arms were joined to the ends of the tube by circumferential fillet welds in T-joints, as shown in Fig. 15.

Originally, the tube assembly was braze welded, but welding cost was high and, despite a low (1%) rejection rate on visual inspection, weld reliability under load was poor. A change to shielded metal-arc welding improved weld reliability, and reduced welding cost by 21.5%. Later, the process was changed to semiautomatic gas metal-arc welding; this resulted in the production of welds with still greater reliability by less-skilled operators, and resulted in a 70% reduction in welding cost compared with that for braze welding, and a 62% reduction compared with that for shielded metal-arc welding. Costs and conditions for the three welding processes are summarized in the table that accompanies Fig. 15.

Although fillet size was different (see Fig. 15), the processing sequence was similar for the three welding methods. The tube, sawed to length, was assembled with the lever arms in a holding fixture, the assembly was welded, and the welds were inspected visually.

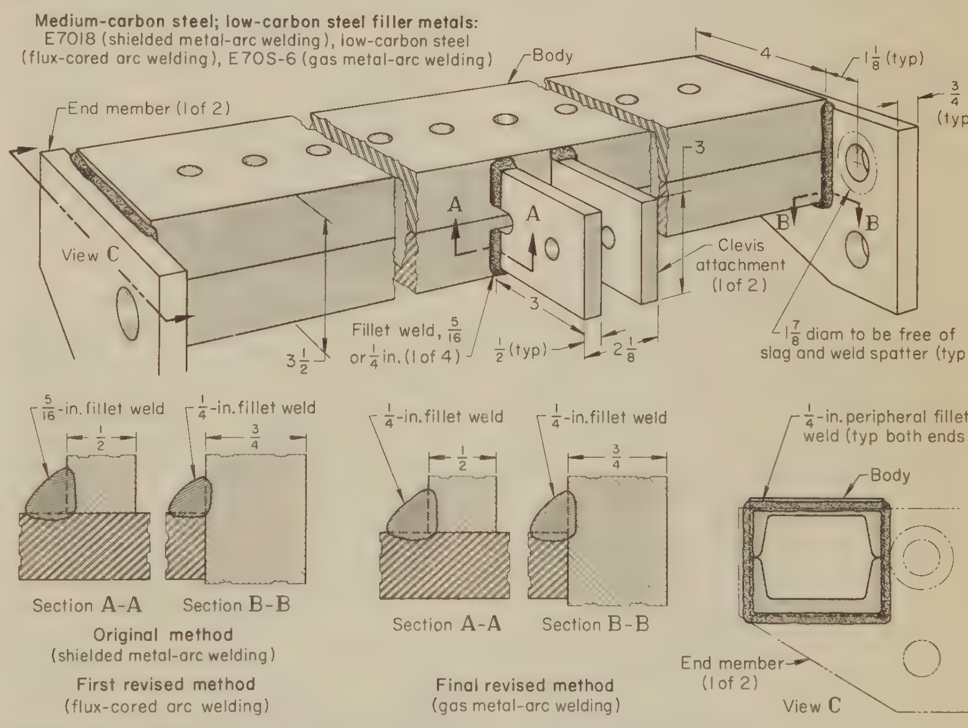
Objectionable hardening did not occur, probably because the fillet size was quite large compared with the wall thickness of the tubing, and so the cooling rate was relatively low.

Example 191. Change From Shielded Metal-Arc and Flux-Cored Arc Welding to the Gas Metal-Arc Process To Eliminate Spatter (Fig. 16)

The medium-carbon (0.45 to 0.55%) steel weldment shown in Fig. 16 is a hitch assembly used as a connector between a tractor and a heavy-duty farm implement. Specifications required that an area 1⅞ in. in diameter on the inside faces of the end members, surrounding two holes for the insertion of hitch pins, be completely free of slag and weld spatter.

Originally, the fillet welds joining the end members and clevis attachments to the body of this assembly were made by the shielded metal-arc process, using E7018 electrodes at 275 amp (dcrp) and 30 volts. Shielded metal-arc welding, though, resulted in excessive slag and weld spatter, whose removal entailed shot blasting, which added to the cost of making the part. Moreover, deposition rate was low.

In an unsuccessful attempt to avoid the difficulty, the process was changed to flux-

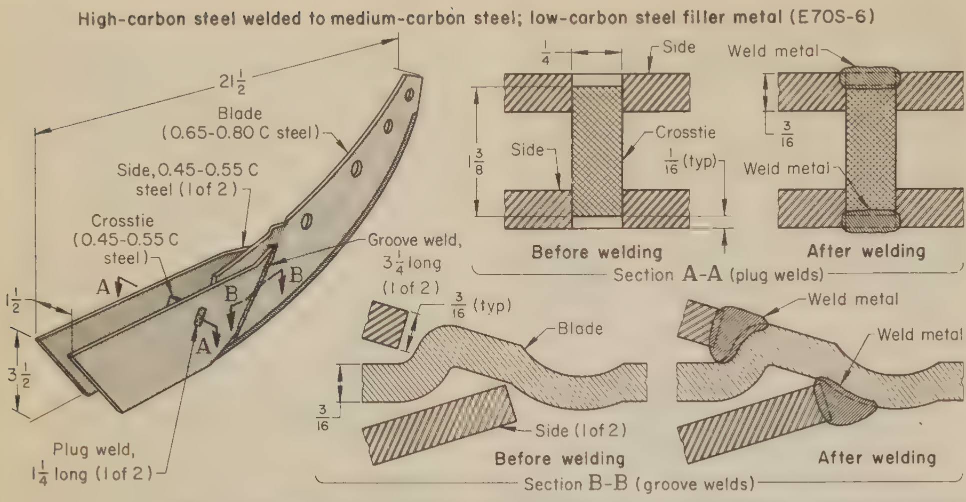


Conditions for Semiautomatic Gas Metal-Arc Welding

Joint type	T	Shielding gas	95% A – 5% O_2, at 30 cfh(b)
Weld type	Fillet	Current	270 amp, dcrp
Welding position	Horizontal	Voltage	28 v
Power supply	300-amp rectifier(a)	Stickout	½ in.
Wire feed	Attached to power supply	Electrode-wire speed	375 ipm
Electrode holder	Hand held, 300 amp	Preheat and postheat	None
Electrode wire	0.045-in.-diam E70S-6	Production rate	50 weldments per 8-hr shift

(a) Constant-voltage type. (b) Supplied from central bulk storage.

Fig. 16. Tractor-hitch weldment for which semiautomatic gas metal-arc welding, under the conditions given in the table, eliminated slag and weld spatter, which had entailed shot blast cleaning after shielded metal-arc and flux-cored arc welding (Example 191)



Conditions for Semiautomatic Gas Metal-Arc Welding

Joint types	Butt and T	Shielding gas	95% A – 5% O_2, at 29 cfh(b)
Weld types	Groove and plug	Current	260 amp, dcrp
Welding position	Flat (15° inclination)	Voltage	29 v
Power supply	300-amp rectifier(a)	Stickout	½ in.
Wire feed	Attached to power supply	Electrode-wire speed	325 ipm
Electrode holder	Hand held, 300 amp	Welding speed	14 ipm(c)
Electrode wire	0.045-in.-diam E70S-6	Preheat and postheat	None

(a) Constant-voltage type. (b) Supplied from bulk storage. (c) Welding speed by the shielded metal-arc process had been 5 to 7 in. per minute.

Fig. 17. Runner for a seed-planter unit, and details of joints for which welding and finishing times were reduced by changing from shielded metal-arc welding to semiautomatic gas metal-arc welding, under the conditions given in the table (Example 192)

cored arc welding, using cored low-carbon steel electrode wire at 375 amp (dcrp) and 29 volts. Although deposition rate was increased over that in shielded metal-arc welding, weld spatter was still excessive enough to entail shot blast cleaning. In addition, fillet legs were unequal, and ingredients in the flux caused green paint that was applied to the completed weldment to turn yellow when dried.

Next, some minor design changes, including slight changes in the side pieces and in the holes in the box section, were made so that welding could be done by the gas metal-arc process. Welding conditions are given in the table with Fig. 16. Quality of the welds was completely satisfactory, and the need for postweld cleaning was eliminated. In addition, there was a saving of 11.175 hr per 100 weldments compared with shielded metal-arc welding. (Annual production was 3850 weldments.)

Before welding, the end members of the hitch assembly were gas cut, and the hitch-pin holes were hot pierced and reamed. The two clevis-attachment members were blanked and pierced in a punch press. The boxlike body had been fabricated as a welded subassembly from two 4-in. structural channels that were pierced before being welded together.

The five components were assembled in a holding fixture, and securely clamped and tack welded. Then the assembly was removed and placed on a worktable for welding. Because the fixture was the same as that employed for shielded metal-arc and flux-cored arc welding, the change to gas metal-arc welding entailed no additional fixturing cost.

To obtain high-quality welds, processing conditions had to be carefully controlled. For consistently sound welds with minimum porosity, the work-metal surfaces had to be free of rust, oil and grease. This was ensured by shot blast cleaning before welding. Heat input had to be controlled, to minimize grain growth and brittleness in the weld metal due to an increase in the carbon content of the weld metal by dilution from the base metal. Welding voltage was maintained within 2 volts, and current was restricted to a maximum rise of 10% above the original value. Stickout was maintained at ½ in., −0, +⅛ in., to control weld-bead shape and to eliminate porosity and spatter. The contact tip was set ⅛ to 3/16 in. inside the nozzle; this retraction afforded optimum control of gas coverage of the weld puddle. To avoid interruption of gas coverage, no fans or drafts were permitted in the welding area.

The size of the fillet welds joining the clevis attachments to the body of the assembly was reduced from 5/16 to ¼ in. for gas metal-arc welding (see Fig. 16). The penetration for the ¼-in. weld beads was greater than for the 5/16-in. beads previously specified, and when a section was cut, polished and etched for examination, the smaller bead, although visually ¼ in. on top, was actually equal to a 5/16-in. fillet when measured through the throat.

The following example illustrates how a change from shielded metal-arc to semiautomatic gas metal-arc welding, for joining a high-carbon steel (0.65 to 0.80% carbon) blade to side frames and crosstie bars made of medium-carbon steel (0.45 to 0.55% carbon), reduced welding, finishing and rework time and produced joints capable of withstanding severe shock and impact in service.

Example 192. Change From Shielded Metal-Arc to Semiautomatic Gas Metal-Arc Welding That Reduced Repair and Finishing Time (Fig. 17)

A runner for a seed-planter unit, shown in Fig. 17, was subjected to severe abrasion during its use in cleaving soil, usually to a depth of 3 to 4 in. In addition, the runner had to sustain the occasional impact that resulted from contact with stones.

Originally, shielded metal-arc welding was used for joining the components of the runner assembly. Despite the use of small (⅛-in.-diam) low-hydrogen electrodes for control of penetration and bead size, 15 to 20% of the weldments required rework, which entailed an excessive amount of grinding, because of melt-through and overwelding. In addition, welding speed was only 5 to 7 in. per minute.

When the process was changed to semiautomatic gas metal-arc welding, under the conditions given in the table with Fig. 17, grinding time was reduced by 75%, rework was decreased to a maximum of 2%, and welding speed was more than doubled. The welds were more uniform in quality than the shielded metal-arc welds, being sound, free of slag and inclusions, and tough enough to withstand field use.

The sides and crosstie were blanked and formed in presses from hot rolled 0.45 to 0.55% carbon steel. The blade was blanked cold from hot rolled 0.65 to 0.80% carbon steel, and hot worked to shape. All components were abrasive blast cleaned before being delivered to the welding department.

After the components had been located over pins and clamped, the assembly was inclined 15° from the flat position for welding. The welder used a slightly oscillating movement to control penetration and bead shape. The end of the nozzle of the electrode holder was held at a distance of about ½ in. from the workpiece; this provided sufficient gas for a porosity-free weld and eliminated excessive spatter. No preheat or postweld heat treatment was used.

Before production was started, three sample weldments were sectioned and etched to check for porosity and cracks. If the samples were satisfactory, the power supply and wire drive were locked and production began. During production, an inspection was made every 30 min, and all defective parts were reworked before production continued.

The change to gas metal-arc welding resulted in a 25% reduction in cost per unit. For every hundred units, welding time was reduced by 2.013 hr and grinding time was reduced by 2.632 hr. With this total saving of 4.645 hr per 100 units, and an annual production of 9000 units, the change to gas metal-arc welding saved 418 hours of production time per year.

Although neither preheating nor postweld heating was used in producing the weldment described in the preceding example (which had one component made of steel containing 0.65 to 0.80% carbon), preheating and postweld heating are ordinarily used. As-welded joints in a steel containing 0.80% carbon should be employed with great caution, because of low notch toughness in the heat-affected zone.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding (discussed in detail in the article that begins on page 113) is less frequently used for joining carbon steel than for high-alloy steels and nonferrous metals.

With gas tungsten-arc welding, as with other welding processes, the use of automatic methods generally is desirable (provided the production volume is great enough to justify the equipment cost), because automatic welding usually increases the uniformity and controllability of weld quality and decreases manufacturing time.

The example that follows describes an application in which a change from manual to automatic gas tungsten-arc welding resulted in improved weld quality and increased production rate.

Example 193. Automatic Gas Tungsten-Arc Welding of Medium-Carbon Steel Tubes to Tube Sheet Overlaid With Low-Carbon Steel (Fig. 18)

Fillet welds joining tubes to tube sheet for use in heat exchangers in feedwater heaters (see Fig. 18) were formerly made by manually rotating a piloted gas tungsten-arc torch centered in the tube hole. Two passes were made around the 3/16-in. tube projection to form a fillet weld, each pass fusing a preplaced filler-wire ring. Although the welds were acceptable, they

lacked uniformity; weld size and contour depended largely on the skill of the operator in rotating the torch at a constant speed for proper fusion of the filler-wire ring. In addition, production rate seldom exceeded 80 welded joints per 8-hr shift.

The substitution of a new procedure, using fully automatic gas tungsten-arc welding equipment under the conditions tabulated with Fig. 18, made it possible to obtain uniformly high-quality welds with good reproducibility. Defects that required rework were few, and production rate increased to an average of 190 welded joints per 8-hr shift.

The automatic equipment included a custom-built gas tungsten-arc welding head that was motor driven to rotate around a water-cooled stationary pilot inserted in the tube hole. Cold filler-metal wire was supplied to the arc from a spool, through a wire-feed drive and an adjustable wire-guide tip, all of which rotated with the welding head. This equipment, together with the slide mounting for horizontal and vertical positioning of the welding head to the tubes, is shown in Fig. 18.

Other equipment features essential to the procedure included: (*a*) an electric gage for accurate positioning of the tip of the tungsten electrode before the first pass was started; (*b*) automatic control of the flow of cooling water for the torch pilot, and of the argon shielding gas; (*c*) an indexing system that automatically retracted the tungsten electrode between passes; (*d*) a 300-amp, constant-current rectifier power supply with high frequency and slope control; and (*e*) an electronic programer with sequence timers, to coordinate the weld cycles for preweld gas (prepurge), arc initiation, weld time per pass, arc decay, postweld gas (postpurge), and cooling-water flow.

The tube sheet had been surfaced with a low-carbon steel overlay of ⅛-in. minimum thickness after machining (see Example 195). The carbon content of the overlay was held to 0.15% maximum, to provide a more ductile heat-affected zone on the tube sheet, since the tube-sheet forging before cladding contained as much as 0.35% carbon.

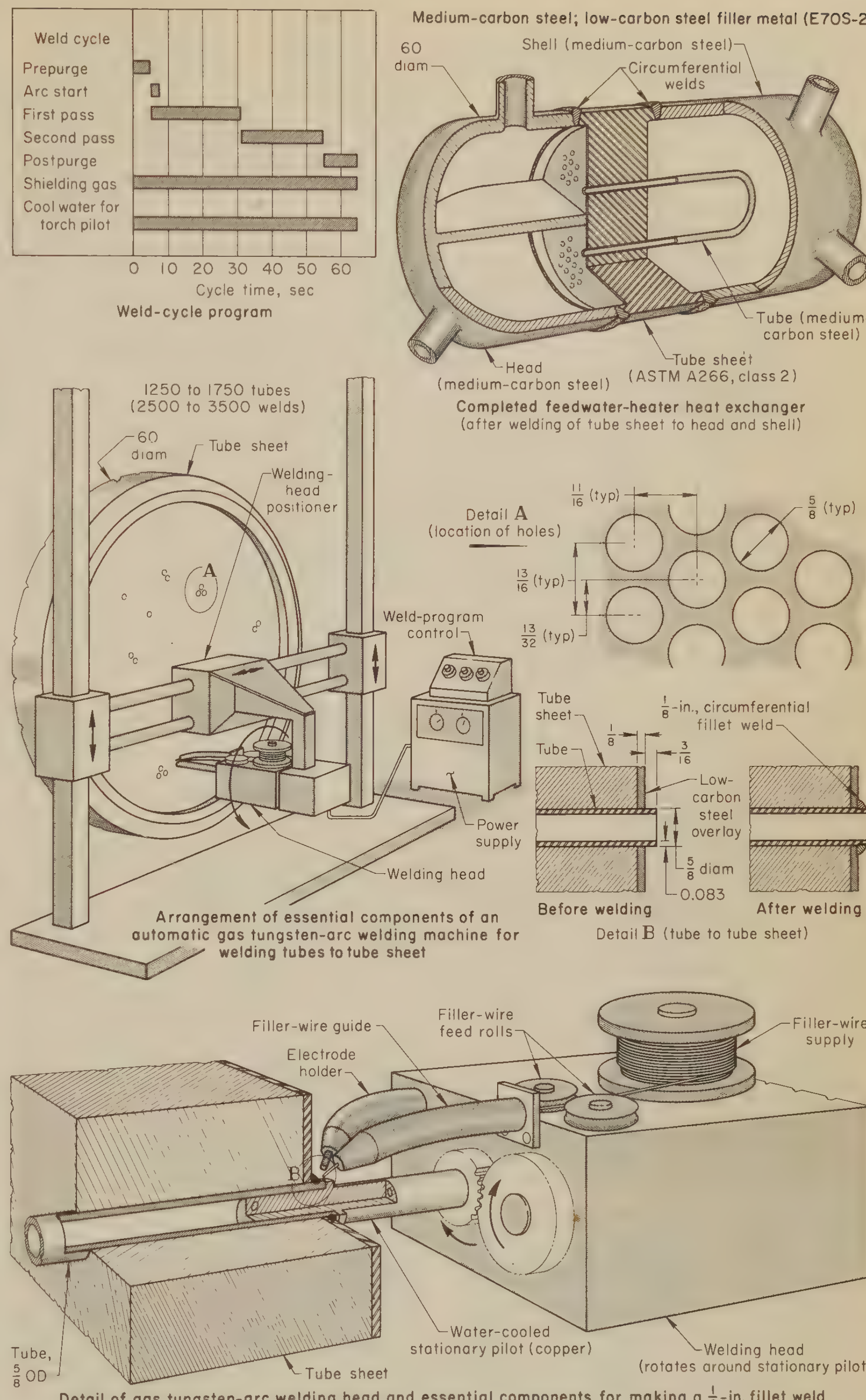
Before assembly, tubes and tube sheet were solvent cleaned, and rigid cleanness was maintained during welding. With tubes in place, the tube sheet was preheated to slightly above room temperature (to 100 F). The welding-head pilot was centered in a tube, and the tungsten electrode and wire-guide tip were properly positioned. Settings for water and gas flow rates, filler-metal feed, rotational speed, welding current, high frequency, and slope control were adjusted for correct values. Finally, the various settings of the timers to control the sequencing of the complete two-pass weld cycle were adjusted on the control panel of the programer, and the weld cycle was initiated by pushbutton. After each weld, the welding head was repositioned for welding the next tube, and the cycle was repeated. The weld-cycle program is shown at the upper left in Fig. 18.

After assembly and welding of the completed tube bundle in the vessel chamber (see view at upper right in Fig. 18), welds were tested hydrostatically, at a pressure of 7300 psi (chamber design pressure was 4500 psi). Welds were also inspected visually for apparent defects and mass-spectrometer Freon tested for leaks.

Surfacing Applications

Although any arc welding process can be used for surfacing by welding, the submerged-arc process, mainly because of the high deposition rate of which it is capable, is generally preferred if the shape of the workpiece is such that submerged-arc welding can be used.

For worn surfaces such as cylindrical bearing journals, restoration by welding to replace the material lost by wear,



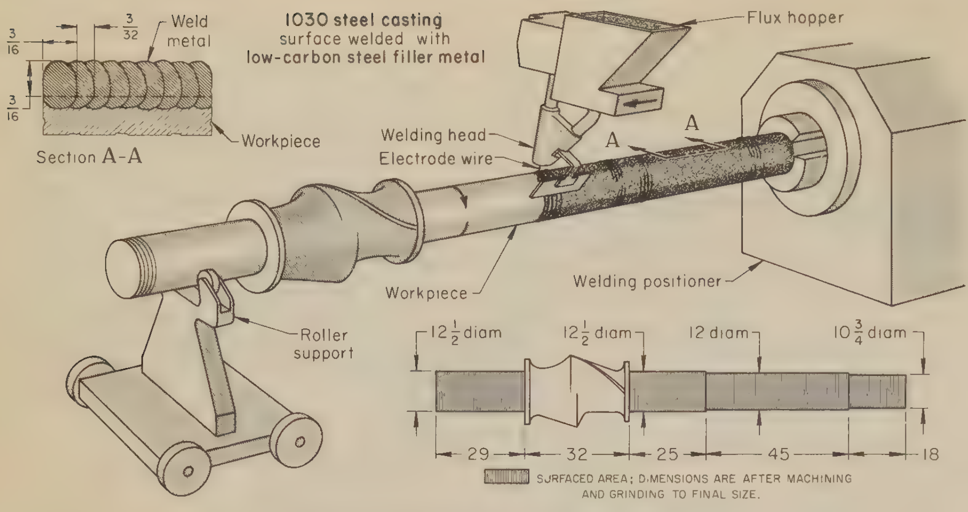
Conditions for Automatic Gas Tungsten-Arc Welding

Joint type	Circumferential T	Filler-wire feed	20 ipm
Weld type	Fillet	Shielding gas	Argon, at 15 cfh
Welding position	Horizontal-fixed pipe	Current	140 to 150 amp, dcsp
Preheat temperature	100 F	Voltage	9 to 11 v
Power supply	300-amp rectifier(a)	Arc starting	High frequency
Electrode holder	Orbiting; argon-gas cooled	Number of passes	Two
Electrode	3⁄32-in.-diam EWTh-2	Welding speed	5 ipm
Filler metal	0.030-in.-diam E70S-2 wire	Total time per two-pass weld	1¼ min

(a) Constant-current type, with high-frequency generator, slope control, and sequence timers

The use of the orbital welding setup shown schematically here, in which the welding head was automatically rotated, replaced an earlier procedure employing manual rotation. The change to automatic welding increased reproducibility and more than doubled production rate.

Fig. 18. Automatic gas tungsten-arc welding of tubes to tube sheet (Example 193)



Conditions for Submerged-Arc Surface Welding

Weld type	Surfacing	Current	500 to 550 amp, dcrp
Surface preparation	Cleaning	Wire feed	Automatic
Process	Submerged-arc welding	Welding speed	13 ipm
Welding position	Flat, rotated	Bead overlap	50%
Electrode	3/16-in.-diam wire(a)	Arc time per rotor	15 hr
Flux	MIL-F-19922 (1 Apr 1958), MIL-B-20	Postheat	1200 F, 4 hr; furnace cool, 12 hr
Voltage	28 to 30 v	Finishing	Machining and grinding to size

(a) Composition, 0.15 C, 2.00 Mn, 0.03 Si, 0.024 S, 0.017 P, 0.53 Mo

Fig. 19. Setup for submerged-arc surface welding to rebuild worn cylindrical surfaces of a mixer rotor (Example 194)

followed by machining to size, may cost much less than replacement by a new part, as is shown in the next example.

Example 194. Use of an Overlay on Cylindrical Portions of a Shaft To Rebuild Worn Surfaces (Fig. 19)

The cast 1030 steel rotor shown in Fig. 19 was part of a Banbury mixer used in a rubber-production line. This rotor had become severely worn on the cylindrical journal surfaces and on the area of the shaft at which gears were keyed. The rotor was rebuilt by welding and machining for about $2000; a new rotor would have cost $6000.

The worn surfaces were built up by submerged-arc welding, as shown in Fig. 19. The rotor was driven from one end in a horizontal position by a conventional welding positioner, and was held at the opposite end by a roller support. The shaft was turned at a surface speed of 13 in. per minute. The total length of built-up area was 117 in., and total arc time for surfacing the rotor was 15 hr. Additional welding conditions are given in the table with Fig. 19.

Because the rotor was covered with rubber residue and grease, before surfacing it was cleaned by abrasive blasting, after which the worn surfaces were lightly machined (1/16 in. removed) on a lathe, without cutting fluid.

The bead was deposited by an overlap technique. The rotor was turned so that a circumferential weld bead was deposited. At the end of each revolution, the welding head was indexed to make the next bead overlap the last by half a bead width. The rotation of the shaft continued during indexing. The result was an overlay composed of a continuous weld bead with 50% overlap — just as would have been achieved by continuously advancing the bead as the journal turned, but the indexing method did not require an interlock between feed and speed.

After welding, the completed rotor was furnace heated at 1200 F for 4 hr and furnace cooled. The welded areas were then machined and ground to size and the rotor was returned to the mixer.

In the example that follows, a low-carbon steel surface weld was deposited on a tube sheet forged from medium-carbon steel to provide a surface more compatible with the medium-carbon steel tubes to which the forged tube sheet was subsequently welded.

Example 195. Submerged-Arc Surfacing of a Medium-Carbon Steel Forging With Low-Carbon Steel for Later Welding to Medium-Carbon Steel Tubes (Fig. 20)

The tube sheet shown in Fig. 20, forged from ASTM A266, class 2, steel (0.35% max carbon), is typical of those used in feed-water-heater heat exchangers.

Originally, medium-carbon steel tubes were fillet welded directly to bare (unclad) tube sheets, but the welds were hard, and had little ductility, as a result of carbon pickup from the tubes and the tube sheet, and also were porous. The porosity in the welds was attributed to the presence of dissolved gases in the forged tube sheet. The hardness and porosity of the welds often led to cracking and leaks in service. To minimize these problems, a low-carbon steel overlay was deposited on the surface of the tube sheet; the carbon in the overlay did not exceed 0.15%, and the deposit was clean and free of gases that could cause porosity. As a result, subsequent tube-to-tube-sheet welds were sufficiently strong, ductile and nonporous to provide sound, leaktight joints in service. The application of the overlay by multiple-electrode submerged-arc welding is shown in Fig. 20; welding conditions are given in the accompanying table. Qualification of procedure and welders was in accordance with Sections III and IX of the ASME Boiler and Pressure Vessel Code.

After the forged tube sheet had been machined, the center of one of the flat faces was surfaced with linear beads in a 13-to-16-in. square (see operation 1 in Fig. 20). Then, the square was machined so as to obtain a circle of overlay 12 to 15 in. in diameter (see operation 2 in Fig. 20). Outside this circle, the overlay was extended to the rim of the tube sheet by the deposition of overlapping beads in a circular pattern. The circular weld beads, consisting of a single layer nominally 1/4 in. thick, were overlapped 40 to 50% (see operation 3 in Fig. 20).

To develop the desired tracking for deposition of the circular beads, the welding head was mounted on a carriage with vertical and horizontal adjustments. It was fed across the surface of the tube sheet from the central overlay disk to the rim area while the work was rotated at a rate adjusted to produce the necessary overlap (see the welding setup in the upper part of Fig. 20). After welding, slag removal, and a stress-relieving heat treatment, the tube sheet was machined to provide an overlay thickness of 1/8 in. minimum (see operation 4 in Fig. 20).

After machining of the overlay, the tube sheet was ultrasonically inspected, and repaired if necessary. The overlay was required to have 100% bond with the tube sheet, and to be completely free of cracks. Some random slag inclusions or incomplete fusion between beads, if no more than 1/4 in. long, were considered acceptable.

The tube sheet then was drilled and vapor degreased, and the tubes were inserted for welding (see Example 193 for a description of that operation). The amount of rework required for correcting defective tube welds was minimal when tube sheets were surface welded with the low-carbon steel overlay. Over a period of four years, approximately 150,000 tube welds were made using clad tube sheets, and no leaks occurred in service.

Examples in Other Articles

In addition to the 15 examples of practice in this article, there are 36 examples in other articles in this volume that deal with arc welding of hardenable carbon steels. Table 3 directs the reader to those 36 examples, and identifies the steels and welding processes used in the applications they describe.

Carbon content, manganese content, and content of residual alloying elements determine the hardenability (and influence the susceptibility to weld cracking) of carbon steel. Cooling rate determines how much hardening will be attained in the weld area. Sec-

Table 3. Examples in Other Articles in This Volume That Describe Arc Welding of Hardenable Carbon Steels

Steel	Process(a)	Example No.
AISI-SAE Steels		
1024	SAW	69
1030	SMAW	160
1035	SAW	76
1040	GMAW	78
	SAW	154
1045	FCAW	20, 33, 40
	GMAW	156
1055	FCAW	20
Medium-carbon(b)	SAW	73, 150, 155
ASTM Steels		
A27, grade 65-35	SAW	50
A36	SAW	64, 77
A53(c)	SAW	52
A53, grade A	SAW	53
A53, grade B	SAW	50
SA-106, grade B(d)	GTAW	128
A234, grade WPA	SAW	53
A235, class C1	SAW	62
A285(c)	GMAW	91
	SMAW	5
A285, grade C	FCAW	24, 25
	SAW	56, 70
A515(c)	FCAW	23
A515, grade 70	SAW	47, 49, 51, 54, 55, 57, 61, 66, 365
	EGW	369
A516	SMAW	5
A537	SMAW	5

(a) EGW, electrogas welding; FCAW, flux-cored arc welding; GMAW, gas metal-arc welding; GTAW, gas tungsten-arc welding; SAW, submerged-arc welding; SMAW, shielded metal-arc welding. (b) Examples do not identify steels by AISI-SAE numbers. (c) Grade not specified in example. (d) Related to A106.

tion thickness has a marked effect on cooling rate. In arc welding, the heat is dissipated rapidly in thin sections, so that susceptibility to cracking is low. In thicker sections, the mass of metal (unless preheating was used) serves effectively as a quench, thus producing martensite.

All other conditions being equal, the welding process used has a significant effect on whether a given steel hardens from welding. Of all the arc welding processes, electrogas welding provides the slowest cooling rate (and least hardening). Because of its high heat input and the blanketing effect of the flux, submerged-arc welding ranks next. Faster cooling rates are obtained in the other arc welding processes.

Twelve of the examples listed in Table 3 deal with AISI-SAE steels that are generally accepted as hardenable carbon steels; the others deal with steels bearing ASTM designations. For most of these ASTM steels, carbon and manganese contents are specified as maximums. For instance, 0.3% max carbon is specified for ASTM A27 steel castings (Example 50), thus allowing considerable latitude in hardenability.

ASTM steel A36 (Examples 64 and 77) is specified for a variety of product forms. Although the carbon content is specified as 0.26% max, in some product forms the manganese content can be as high as 1.20%. Thus, under some conditions A36 has moderate hardenability.

ASTM steel A53 (Examples 50, 52 and 53) is specified for welded and seamless pipe. For some grades, the carbon content may be as high as 0.30% and the manganese as high as 1.20%.

Steel SA-106 (Example 128) is related to ASTM A106. Depending on the grade within the general specification, the carbon content may be as high as 0.35% and the manganese as high as 1.06%.

Steel covered by ASTM A234 (Example 53) is exclusively for fittings, and the composition and hardenability are essentially the same as those of A285 (see second-next paragraph).

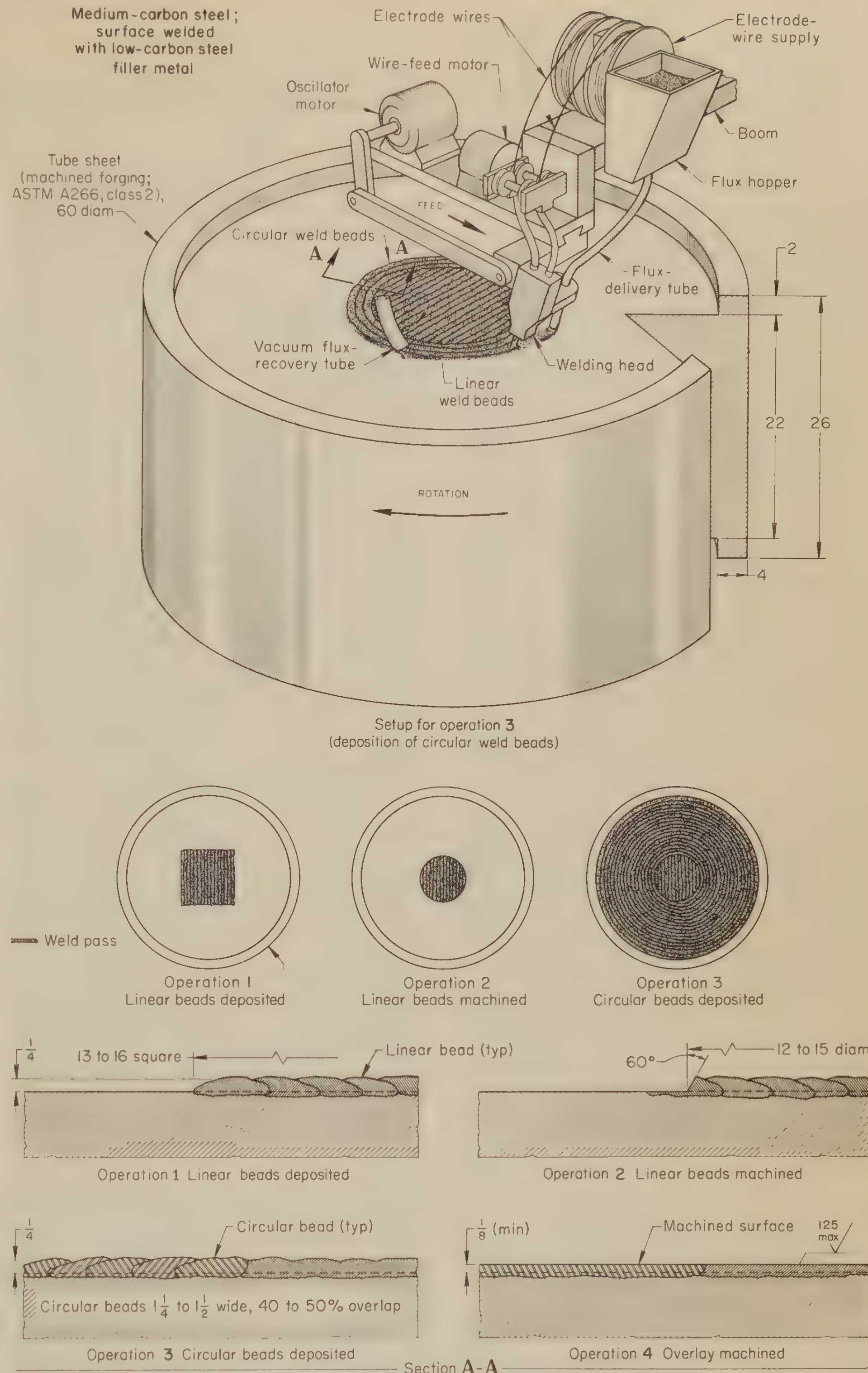
Carbon steel forgings made to ASTM A235 (Example 62) require maximum carbon content of 0.35% if they are to be welded. Thus, a broad range of hardenability is permitted.

ASTM A285 (Examples 5, 24, 25, 56, 70 and 91) covers carbon steel plates having maximum carbon and manganese contents of 0.28 and 0.90%, respectively. Thus considerable hardening can occur in welding.

ASTM A515, represented by 11 of the examples in Table 3, covers steel plate for boilers and pressure vessels. Carbon and manganese contents can be as high as 0.31 and 0.90%, respectively; thus, A515 may have greater hardening capability than A285.

Steel A516 (Example 5) is similar in composition to A515, except A516 has maximum carbon and manganese contents of 0.27 and 1.20%, respectively.

Heat treated steel plates covered by ASTM A537 (Example 5) have established ranges for manganese and silicon of 0.65 to 1.40% Mn and 0.13 to 0.55% Si. Maximum carbon content for A537 is specified at 0.24%. If both carbon and manganese are near the allowable maximums, A537 is capable of developing considerable hardness in welding.



Multiple-Electrode Submerged-Arc Surface Welding, With Oscillation(a)

Weld type	Surfacing	Stickout	2 in.
Surface preparation	Machine to 125-micro-in. finish, and solvent clean	Welding position	Flat(d)
Power supply	Rectifier or motor-generator(b)	Current each electrode	550 to 600 amp, dcsp
Wire feed	Automatic, variable speed(c)	Voltage	37 to 39 v
Electrode wire	5/32-in.-diam low-carbon steel (0.03% carbon max)	Welding speed	7 to 8 ipm
		Deposition rate	20 to 25 lb per hour
		Preheat temperature	350 F, min(e)
Flux	Bonded, neutral	Postheat (stress relieving)	1150 F, 1 hr

(a) Two electrodes; spacing, 1/4 in. Oscillation width, 1 in.; speed, 40 to 45 strokes per minute. (b) Rated at 750 amp; drooping voltage characteristic. (c) With twin feed rolls and wire straighteners on a common shaft. (d) Workpiece was rotated on a positioner for deposition of circular weld beads, as shown. (e) While being rotated, workpiece was preheated locally, with large portable torches; temperature was determined by use of crayon indicators.

Fig. 20. Use of submerged-arc welding for deposition of a low-carbon steel overlay on a medium-carbon steel tube sheet, to increase ductility and soundness of subsequent fillet welds joining the tube sheet to medium-carbon steel tubes (Example 195)

Arc Welding of Alloy Steels

*By the ASM Committee on Welding of Hardenable Steel**

ACCEPTABLE RESULTS in the welding of alloy steels are related directly to the metallurgical structures that are produced in the weld metal and in the heat-affected zone of the base metal during and after welding. These structures are governed by the thermal cycles that occur during welding.

Hardness. As in the welding of hardenable carbon steel (see the preceding article in this volume), martensite is the metallurgical constituent of principal concern in the welding of alloy steel. The hardness of martensite depends on its carbon content, as shown in Fig. 1 on page 187 in the article on Arc Welding of Hardenable Carbon Steels. Excessive hardness, and accompanying brittleness, is a major cause of weld cracking.

Carbon and low-alloy steels that have the same carbon content will have the same maximum hardness when cooled rapidly enough to achieve maximum martensite in the microstructure. In Fig. 1(a) below, the maximum hardness is shown at the 1⁄16-in. end-quench distance for five alloy steels that have the same nominal carbon content of 0.40% (maximum of the specification range is 0.44% for each steel). Despite the major differences in alloy content and hardenability among these five steels, each steel has the same maximum hardness, Rockwell C 60. The two steels in Fig. 1(a) that have slightly lower maximum carbon contents (4037H and 1038H) have slightly lower maximum hardnesses, as shown.

Ten 41*xx*H steels are compared in Fig. 1(b). Each of these steels has essentially the same alloy content (nominally 1% Cr and 0.20% Mo, with 0.80% Mn; there are slight variations through the series), but the steels range in maximum carbon content from 0.23% for 4118H to 0.65% for 4161H. As shown in Fig. 1(b), in this series of ten chromium-molybdenum steels, the maximum hardness (at the 1⁄16-in. end-quench distance) increases from Rockwell C 48 to 65 as maximum carbon content increases from 0.23 to 0.65%.

In the welding of high-strength low-alloy steels that contain not more than 0.25% carbon (see page 207), welding procedures are deliberately chosen so that martensitic structures are obtained. These steels are intended to be welded in the quenched-and-tempered condition. The low-carbon martensite formed during postweld cooling has desirable strength, and the as-welded joints have adequate toughness. However, as carbon content is increased, the higher-carbon martensites that are formed are harder and less ductile in the untempered condition, and are a major contributor to the cold cracking of welds.

Higher hardenability is the one characteristic that differentiates alloy steels as a class from plain carbon steels, and is the principal complication in welding. With higher hardenability, martensite forms at lower cooling rates.

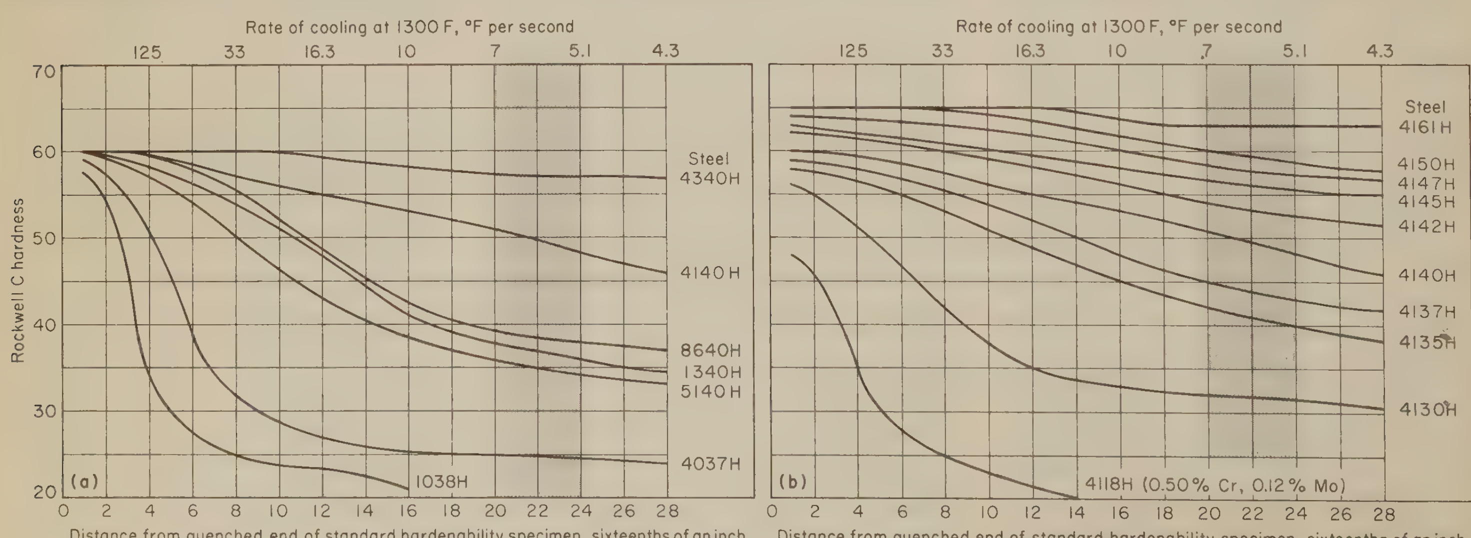
As the alloy content or the carbon content of steel is increased, the hardenability is increased. Figure 1(a) shows the maximum hardenability of 1038H carbon steel and six widely used alloy steels of 0.40% nominal carbon content. The maximum hardenability of carbon steel 1038H (bottom curve) is low; that is, hardness decreases rapidly as cooling rate (top scale) decreases. As various amounts and combinations of alloying elements (Cr, Ni, Mo, Mn) are added to steel containing 0.40% carbon, the maximum hardenability increases to that shown for 4340H. Figure 1(b) shows the large effect of increasing carbon content on maximum hardenability in 41*xx*H steel. The effect on hardenability of increasing carbon from 0.23% (the maximum in 4118H) to 0.65% (the maximum in 4161H) in these alloy steels is somewhat greater than the effect, shown in Fig. 1(a), of increasing total alloy content (Mn, Cr, Mo, Ni) from 1% (maximum in 1038H) to 4.15% (maximum in 4340H).

Hardenability curves such as those shown in Fig. 1 are used primarily for selecting steels for structural members of different thicknesses and in designing appropriate quenching procedures for achieving various cooling rates (see scale across the top of Fig. 1) at various depths below the steel surface in heat treatment. The application of hardenability curves to the welding of alloy steel is largely qualitative, because cooling rates at various locations within the weld metal and the heat-affected zone of the base metal are seldom known with the accuracy that is available for cooling rates in steel sections during quenching in water, oil or air.

In general, the weldability of steel decreases as its hardenability increases, because higher hardenability promotes the formation of martensite under conditions that make cold cracking of the martensitic steel more probable.

In welding, it is seldom possible to achieve cooling rates slower than 5 or 6 °F per second. This cooling rate corresponds to positions of 20 to 24 sixteenths of an inch from the quenched end of the standard end-quench hardenability specimen (see shaded areas of Fig. 1a and 1b). Thus, if the hardness corresponding to this cooling rate

*For a list of the members of this welding committee, see page 187. Most of the 33 examples of practice that are presented in this article were contributed by members of other Metals Handbook welding committees.



(a) Effect of various amounts and combinations of alloying elements in steel with a nominal carbon content of 0.40%, compared with carbon steel 1038H. (b) Effect of carbon content in 41*xx*H alloy steel (nominal 1% Cr and 0.2% Mo, except for 4118H). All data from 1970 SAE Handbook.

Fig. 1. Maximum hardenability of alloy steels and 1038H carbon steel. See text for discussion.

(end-quench distance) for a particular steel is too high to be acceptable in the heat-affected zone of a weldment, the weldment, or at least the zone of excessive hardness, must receive a tempering treatment after welding.

Carbon Equivalent. Several formulas have been developed to assist in evaluating the weldability of alloy steels. These formulas reduce the significant composition variables to a single number, known as the carbon equivalent. One such formula is as follows:

$$\text{Carbon equivalent} = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{15} + \frac{\%Cr}{5} + \frac{\%Mo}{4} + \frac{\%V}{5}$$

Steels having carbon equivalents by this formula of less than 0.40% usually require no preheating or postheating. Steels with carbon equivalents between 0.40 and 0.60% usually require preheating, and steels with carbon equivalents greater than 0.60% may require both preheating and postheating. Because the carbon equivalent is calculated from the base-metal composition and includes no other variables, it is only an approximate measure of weldability or susceptibility to weld cracking. Other factors that contribute to weld cracking must be considered simultaneously, in relation to a specific application.

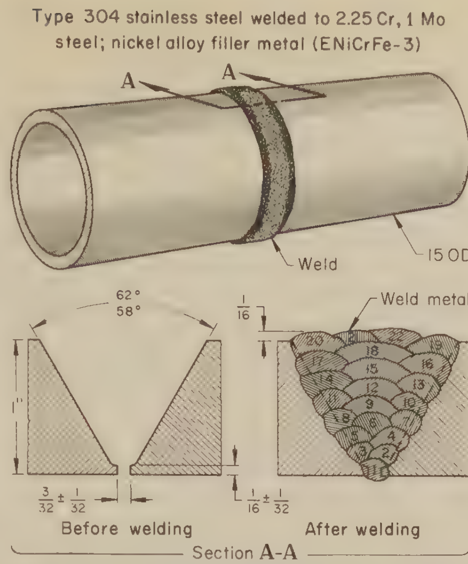
Filler Metal. Filler metals of almost any desired alloy steel composition can be obtained. However, the composition of the deposited weld metal is likely to be quite different from that of the filler metal before welding, depending on how effectively the alloying elements are transferred across the arc. In welding with consumable electrodes, transfer is often less than 75% complete, especially for elements that have high affinity for oxygen. The extent of change in filler-metal composition depends to some extent on the shielding gas used. There is generally less change in composition with argon shielding than with carbon dioxide.

When arc welding with nonconsumable-electrode processes (gas tungsten-arc or plasma-arc welding), there is less change in filler-metal composition, because the filler metal is fed directly into the weld puddle. Often, the filler metal selected to weld an alloy steel differs considerably in composition from that of the base metal, particularly when the base metal is of high hardenability and the objective is to obtain a weld metal of lower hardenability that is less likely to crack.

High sulfur or phosphorus content (from the base metal, the filler metal, or external sources) can cause hot cracking in the welding of alloy steels. The effects of these elements vary with the amounts of other elements present, principally with the carbon and manganese contents. Some advocate a maximum content of sulfur plus phosphorus of 0.025%. In at least one application, a combined sulfur and phosphorus content of 0.020% has been recommended to prevent base-metal cracking in highly restrained joints of 4340 steel. To a considerable extent, the adverse effects of high sulfur can be offset by increasing the manganese content in either the base metal or the filler metal. Resulfurized alloy steels are not recommended for arc welding, but they can be welded (see Example 221, page 230).

In shielded metal-arc welding, the composition of the electrode covering can influence the weldability of high-sulfur steels. Low-hydrogen electrodes E7015 and E7016 have been used for welding resulfurized alloy steels (0.13% max sulfur). Resulfurized alloy steels with high manganese contents are preferred for welding because manganese forms a stable, higher-melting sulfide that counteracts susceptibility to hot cracking caused by sulfur.

Besides base-metal composition, preheating and postheating, the selection of filler-metal composition can be influenced by the coefficient of expansion of the base metal, carbon depletion in the heat-affected zone, and the deposition characteristics of the filler metal. The influence of some of these factors on the selection of filler metal is illustrated in the following example, which describes the use of a nickel alloy filler metal in shielded metal-arc welding of low-alloy steel to stainless steel, without the incidence of cracking or porosity in the weld.



Conditions for Shielded Metal-Arc Welding

Joint type	Butt
Weld type	Single-U groove
Welding position	Horizontal rolled
Number of passes	22
Preheat and interpass temperature	500 F(a)
Postheat	1350 F(b)
Electrode wire	1/8 and 5/32-in.-diam ENiCrFe-3(c)
Power supply	300-amp motor-generator
Current (dcrp) and voltage:	
Tack welding, and pass 1	60 amp, 21 v
Passes 2 and 3	90 amp, 23 v
Passes 4 to 22	120 amp, 24 v

(a) Only the ferritic low-alloy steel side. Heating was by induction. (b) Heated at 1350 F for 1 hr by induction and cooled to 300 F in still air. (c) 1/8-in.-diam electrode wire for passes 1 to 3, and 5/32-in.-diam wire for passes 4 to 22.

Fig. 2. Assembly of a low-alloy steel pipe and a stainless steel pipe that was joined with crack-free welds by use of a nickel alloy filler metal (Example 196)

Example 196. Nickel Alloy Filler Metal for Crack-Free Welding (Fig. 2)

The selection of a filler metal was an important factor in welding a 2¼Cr-1Mo steel pipe (ASTM A387, grade D) to a type 304 stainless steel pipe. This pipe assembly was a component of a steam pipeline that had to withstand cyclic heating and cooling between 1050 F and room temperature. Details of the joint between the 15-in.-OD by 1-in.-wall pipes before and after welding, in 22 passes, by the shielded metal-arc process are shown in Fig. 2. A nickel alloy flux-covered electrode (ENiCrFe-3) was selected in preference to an austenitic stainless steel electrode, for three reasons:

1. The coefficient of thermal expansion (8.5 micro-in. per inch per °F) of weld metal from the ENiCrFe-3 electrode is close to that of the ferritic 2¼Cr-1Mo steel. Thus, during cyclic temperature service, the major differential expansion stresses developed primarily at the stronger interface between the stainless steel pipe and the weld metal, rather than at the weaker interface between the ferritic steel pipe and the weld metal — the location at which such expansion stresses would have developed if a stainless steel electrode had been used.
2. Carbon depletion in the ferritic steel was less when the nickel alloy weld metal was used than when a stainless steel weld metal was used. Therefore, the heat-affected zone of the ferritic steel was not weakened by loss of carbon.
3. The excellent deposition characteristics of the nickel alloy electrode produced a sound, porosity-free weld that was not subject to weld-metal cracking.

The pipe ends were machined to the joint configuration shown in Fig. 2 and wiped clean with a solvent; then the pipes were mounted horizontally on turning rolls for welding. Low-frequency induction heating was used to provide a 500 F preheat for the ferritic pipe. This temperature was maintained, by automatic control, throughout the welding operation.

The joint was tack welded at 6-in. intervals, using a 1/8-in.-diam electrode and the same current and voltage settings as for the first pass (see table of welding conditions with Fig. 2). The edges of the tack welds were thinned by grinding before the root pass, which was carefully deposited to obtain a smooth inside root surface. Each weld bead was deslagged and visually inspected before the next bead was deposited. Immediately after welding, the weld was postheated, by induction heating, to 1350 F for 1 hr and air cooled.

Welds made with the ENiCrFe-3 electrode met bend-test and tension-test requirements of Section IX of the ASME Boiler and Pressure Vessel Code, and also passed visual, dye-penetrant, radiographic and metallographic inspection. Fractures produced in transverse tension tests at room and elevated temperatures were in the base metal away from the heat-affected zones. The welds had markedly better resistance to cracking during thermal cycling than did similar joints welded with type 347 stainless steel electrodes.

Stress-Causing Factors. Local cracking or fissuring in the deposited weld metal or the heat-affected zone occurs either because the strength or the ductility of the steel locally is not sufficient under the conditions of welding to sustain the localized stresses without fracturing. Under conditions of extreme stress, complete failure of the joint may occur during or shortly after welding. However, it is also possible that stresses of lesser magnitude, insufficient to cause instantaneous failure, will generate minute cracks in the weld zone that will enlarge and spread gradually, causing the welded structure to fail in subsequent service.

By far the most significant sources of stress during welding are the thermal gradients, which may generate stresses that exceed the yield strength, especially considering that the yield strength is lower at elevated temperatures than it is at room temperature.

In practice, the stresses are accommodated by movement in the parts of the assembly being welded. This movement may consist of plastic or elastic deformation of the parts, or gross movement of the parts. Thus, conditions that prevent movement of the parts increase the probability of cracking. Therefore, it follows that the thicker and more massive the plates or parts being welded, the more rigid the design; and the higher the hold-down or fixturing loads, the greater is the probability of cracking.

The root pass in massive weldments is especially susceptible to cracking, because the relatively small cross section of weld metal is not strong enough to force the movement of the large mass of base metal.

Restraint in a welded joint is usually imposed by component design, although fixtures that hold the assembly for welding can also contribute. The susceptibility to cracking caused by restraint increases as the hardenability of the base metal or filler metal increases. Thus, cracking caused by restraint is closely related to preheating, postheating, and interpass temperature. The following example describes an application in which fatigue-crack failures in service were traced to rigidity in weldment design and excessive restraint during welding.

Example 197. Prevention of Fatigue Cracks in Welds by Redesigning Weldment for Less Rigidity (Fig. 3)

An upper fifth wheel for a highway semitrailer, when designed as shown at left in Fig. 3, proved unsatisfactory in service because fatigue cracks developed in the welds, made by the semiautomatic gas metal-arc method, at the joints between the longitudinal and cross-member channels. Under a 35,000-lb vertical load on the fifth wheel, the vertical displacement of these joints was ⅜ in. relative to the ends of the cross members. Closer control of weld quality at the junction did not eliminate the cracking, nor did the addition of gussets between the two longitudinal channels and the front cross member. Although deflection under load could have been reduced by increasing the section thicknesses, this was undesirable because of the weight penalty.

The assembly was redesigned to omit the welds that were subject to failure. As shown at right in Fig. 3, a gap was left between the longitudinal and cross-member channels, thereby eliminating the point of overlapping welds and the need for welding in a corner. The bottom plate was made in two pieces, and the longitudinal channels were capped off with an angle. In the improved design, the only attachment between the front and rear sections was a transverse square-groove butt weld that joined the front plate, angle, and rear bottom plate. The groove weld and the gap permitted rotational movement between the longitudinal and cross-member channels.

To verify the simplified design, the entire upper fifth wheel assembly was fatigue tested under a cyclic load of 0 to 35,000 lb at a rate of 19 cycles per minute. The revised assembly design was accepted after withstanding 500,000 cycles without failure. Strain-gage measurements of the stress developed in the metal adjacent to the transverse groove weld by a 35,000-lb load showed it to be 24,000 psi max. This was well within the 43,000-psi fatigue-strength limit (rotating-beam method) generally ascribed to high-strength structural steels of 50,000-psi minimum yield strength.

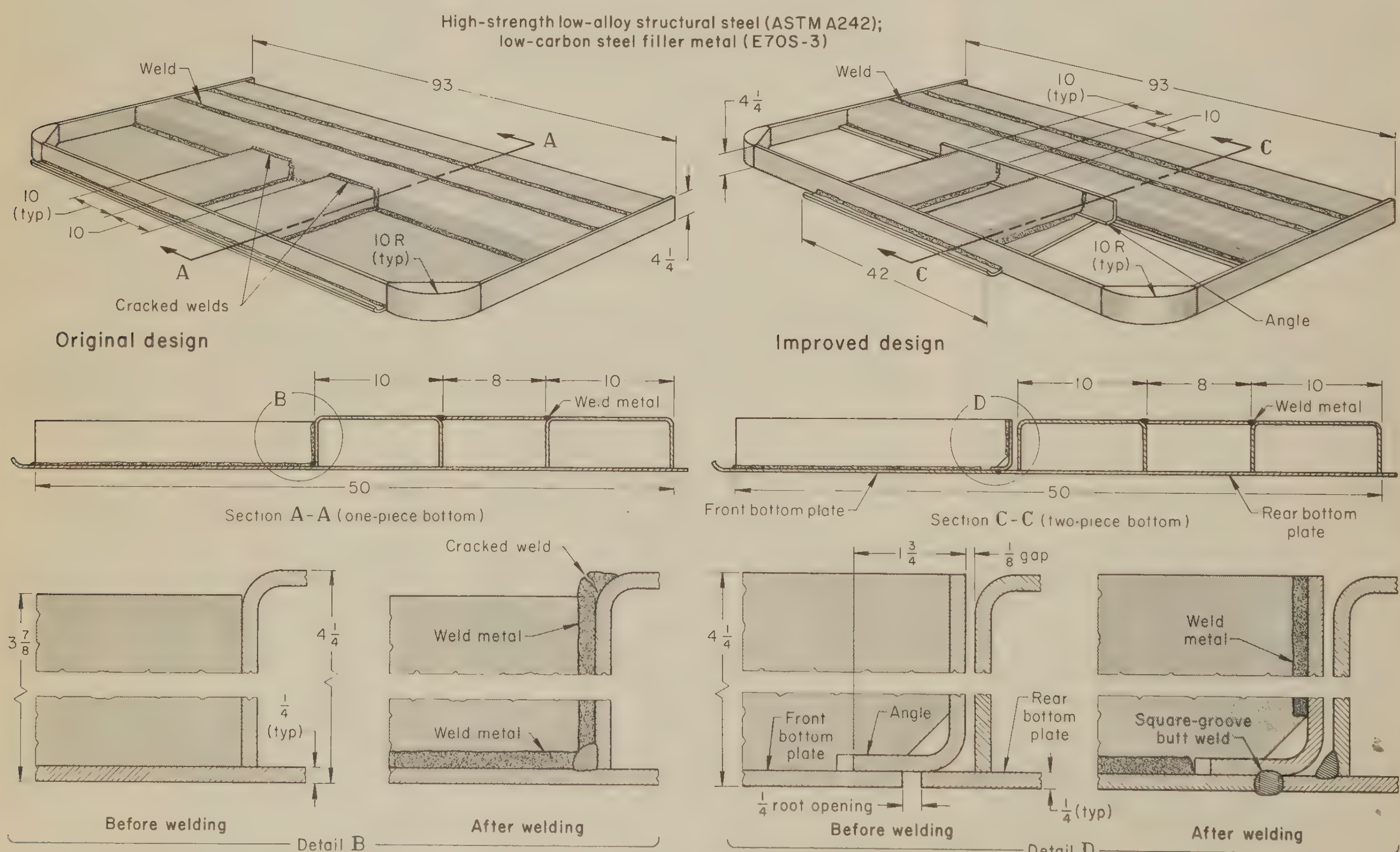
Welding conditions are given in the table with Fig. 3.

Pickup, Dilution and Recovery*

Pickup is the increase in any alloying element in a weld deposit caused by melting and incorporating some of the base metal during welding. Pickup usually occurs when the filler metal is of lower alloy content than the base metal. For example, if a 3% nickel steel is welded with a nickel-free filler metal, the mixture of base metal and filler metal that forms the weld puddle will contain some nickel, perhaps 1%. In a multiple-pass weld, any bead or layer that is directly on the base metal picks up the greatest amount of alloying elements from that metal.

The extent to which the base metal melts controls alloy pickup in the weld metal. This varies somewhat with the

*This section was adapted from pages 435 to 439 in Chapter 15, Welding Alloy Steels, of Volume 2 of "Welding Metallurgy", by George E. Linnert (American Welding Society, 1967).



Conditions for Gas Metal-Arc Welding	
Joint type	Butt and T
Weld type	Square groove and fillet
Welding position	Flat and horizontal
Number of passes	One
Preheat and postheat	None
Fixtures	All components pneumatically clamped in a fixture before welding
Shielding gas	Argon, at 40 cfh
Electrode wire	0.045-in.-diam E70S-3
Electrode holder	Hand held, air cooled
Wire feed	Automatic constant-feed type
Wire-feed rate	300 in. per minute
Power supply	500-amp motor-generator
Current	300 amp, dcrp
Voltage	26 v
Travel speed	12 in. per minute

Fig. 3. Semitrailer upper fifth wheel on which a design change provided less rigid construction, preventing weld failures (Example 197)

different arc welding processes. In many applications of welding alloy steel, the pickup of alloying elements by the weld metal is anticipated, and is utilized to impart certain properties, such as strength, to the weld metal. This practice requires production testing to establish a procedure that will provide the desired pickup.

Dilution is the reduction in alloy content of a weld deposit by virtue of base-metal melting and the incorporation into the weld puddle of melted base metal of alloy content lower than that of the filler metal. Dilution is commonly expressed as the percentage of base metal that has entered the weld metal. If the chemical compositions of the filler metal and the base metal are known, then, by knowing the percentage dilution, the weld metal composition can be calculated. Dilution, or its converse, alloy pickup, can markedly change the composition of weld metal.

The mixing of base metal and filler metal is the most important factor governing the composition of the weld. The extent of the mixing is expressed as the percentage of the entire cross-sectional area of the weld metal, as revealed by a macrosection, that falls within the outlines of the base metal before welding. To measure this percentage, a section is cut through the weld perpendicular to both the direction of welding and the surface of the plates. The cut section is given a rough polish with abrasive paper and is etched to reveal the boundary of the metal that has been melted during welding.

Sections through welds of several types are shown in Fig. 4. The percentage of the entire cross section of weld metal falling within the initial outlines of base metal, called the dilution percentage, is:

$$\% \text{ dilution} = \frac{B + D}{A + B + C + D} \times 100$$

The dilution percentage is high for welds in sheet or thin plate (see lower right view in Fig. 4), for which little filler metal is required. If no filler metal is added, an "autogenous" weld results; dilution is 100%, and the weld composition is essentially the same as that of the base metal (see the "100% dilution" square-groove butt weld in Fig. 4). For bevel-groove welds in thicker plate (upper left view in Fig. 4), the dilution may be as low as 20%. Penetration also has a marked effect on the amount of dilution that takes place (see the fillet welds in Fig. 4).

Depositing the same filler metal under identical conditions of current and speed will result in more dilution when welding on sheet or thin plate than when welding on thick plate, because of the difference in penetration (see lower right pair in Fig. 4). The melting temperature of the base metal also affects dilution. For example, a low-carbon steel electrode will exhibit greater depth of penetration on cast iron (melting point, 2100 to 2200 F) than on steel (melting point, 2750 F) under the same conditions of deposition. Thus, dilution will be greater with cast iron as the base metal.

At one time it was considered generally desirable that the weld metal should have, as nearly as possible, the same composition as the base metal. This is no longer considered a general rule. There are many applications where the filler and base metals differ greatly in composition (see Examples 196 and 210).

Table 1. Solubility of Oxygen, Nitrogen and Hydrogen in Iron

Gas	Solubility (weight %) of gas in: Liquid iron at melting point	Solid iron at melting point	Gamma iron at 1670 F (910 C)	Alpha iron at: 1670 F (910 C)	Alpha iron at: Room temperature
Oxygen ..	0.16	0	...	...	0
Nitrogen .	0.040	0.015	0.020	0.010	0.0001
Hydrogen .	0.0025	0.0006	0.0004	0.0003	0.00005

Recovery is the ratio of the alloy content of the weld deposit to the alloy content of the filler metal or auxiliary material, such as electrode coverings, and is expressed as a percentage:

$$\% \text{ recovery} = \frac{\% \text{ of alloying elements in deposit}}{\% \text{ of alloying elements in filler metal}} \times 100$$

The deposit from a bare consumable electrode containing 0.50% carbon may contain no more than 0.05% carbon (that is, the recovery may be as low as 10%), but if the consumable electrode is covered with flux, the carbon recovery may rise to nearly 100%, depending on the protection afforded by the covering.

Nickel is recovered almost completely when a nickel-containing steel filler metal is used, because nickel has a high boiling point and less affinity than iron for oxygen, nitrogen and other gases that may be present in the welding atmosphere. Copper is also recovered almost completely, for the same reasons. Silicon, though, often is oxidized almost completely from a bare electrode; its recovery can be improved by shielding. Chromium is oxidized to some degree, but to a considerably lesser extent than silicon.

The alloying elements used in steel can be ranked according to extent of oxidation during transfer across the arc, starting with those that have low recovery (are oxidized easily) and ending with those that are recovered almost completely. The order is as follows: aluminum, titanium, silicon, columbium, manganese, vanadium, chromium, tungsten, molybdenum, copper and nickel.

The efficiency of transfer of alloying elements in an electrode, or in a flux covering or core, ordinarily is anticipated by the manufacturer, and compensating amounts are added to offset losses. However, some loss of alloying elements occurs from the molten weld puddle, which includes base-metal alloying elements.

Low recovery of an alloying element may result from the low boiling point (high vapor pressure) of the element, or from its transfer to the slag when slag is present.

Gases

The effect of gases, especially that of hydrogen, on the quality of welds in alloy steels is of major significance. Relatively small amounts of hydrogen in martensite are sufficient to cause underbead cracking. Although both the base metal and the filler metal are potential sources of hydrogen, more significant amounts of the gas are likely to derive from moisture or from flux coverings on electrodes that are not low-hydrogen types. Hydrogen may be introduced from moisture in the surrounding atmosphere or in the shielding gas, from improperly cleaned components, or from improper care of covered electrodes or the fluxes used in flux coverings.

Because of decreasing solubility, the hydrogen in molten metal is rejected as the metal solidifies. For this reason, the hydrogen in weld metal is also a major cause of porosity.

Oxygen, nitrogen, argon, helium, carbon dioxide and carbon monoxide are other gases encountered in welding. Of these, helium and argon are insoluble in steel. Oxygen and nitrogen, as well as hydrogen, are more soluble in molten steel than in solid steel, as shown in Table 1. During freezing, the oxygen dissolved in molten steel may react with carbon from the steel and form bubbles of carbon monoxide, which may be trapped in the solid steel. Similarly, nitrogen coming out of solution may be trapped in the solid steel. Or iron nitride may be formed as a precipitate. In general, however, harm that can result from the other gases listed above is of little significance compared with the damage to the weld area than can be caused by hydrogen.

Welding Process Variables

Consideration of welding process variables necessarily begins with the thermal cycle associated with welding.

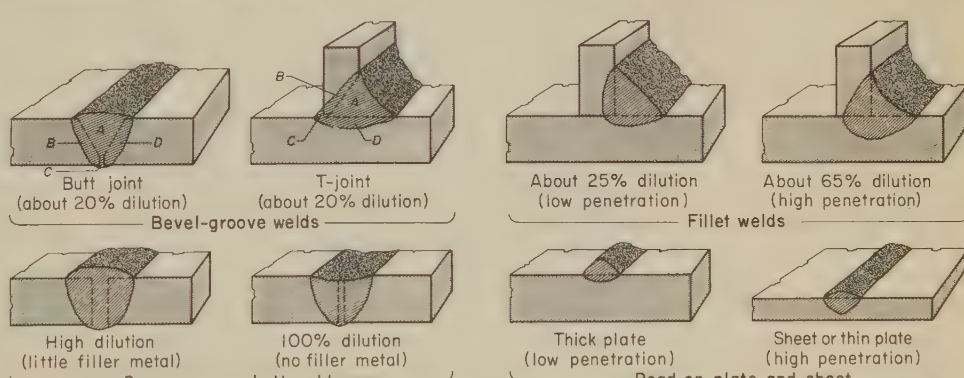
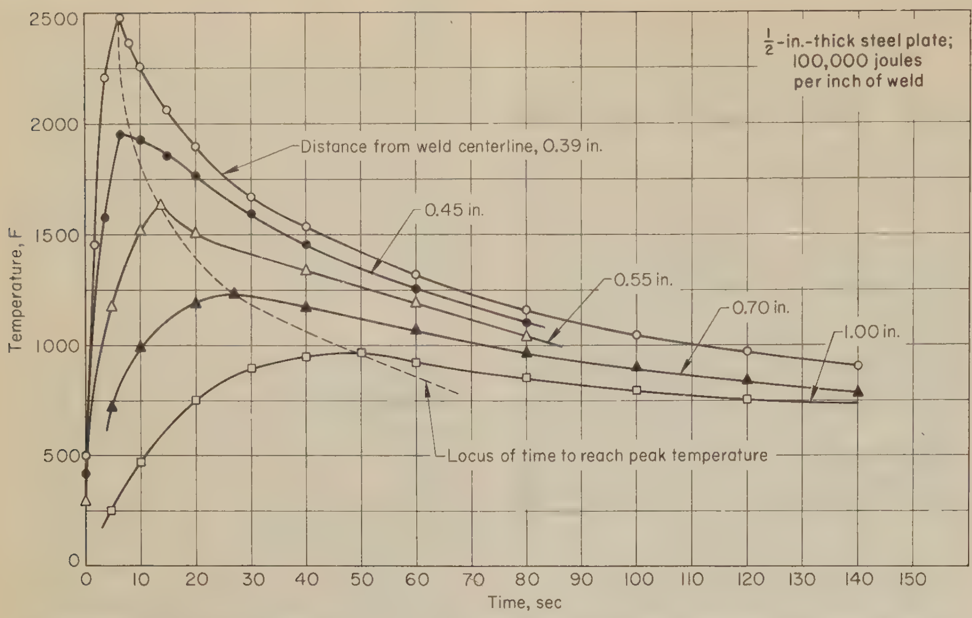


Fig. 4. Effect of filler-metal addition and penetration on weld-metal dilution. See text for dilution-percentage formula, and discussion.



Data are for arc welds made in ½-in.-thick steel plate at room temperature, using a heat input of 100,000 joules per inch of weld. (SOURCE: AWS Welding Handbook, 6th Ed., Section 1)

Fig. 5. Thermal cycles as a function of distance from weld centerline

Several variables affect temperature distribution and metallurgical changes in the vicinity of a weld, notably the heat input of the arc, the initial temperature or preheat temperature of the workpiece, weld design, and the thermal conductivity of the base metal. The heat input provided by the arc is expressed in joules (watt-seconds) per lineal inch of weld and is defined as:

$$H = \frac{E \times I \times 60}{S}$$

where H is heat input (in joules per inch), E is arc voltage (in volts), I is arc current (in amperes), and S is arc travel speed (inches per minute).

Heat input calculated by this formula is an approximation, because heat losses are large. However, it is useful for comparison. Some welding specifications limit heat input, especially for the welding of quenched and tempered alloy steel. Heat input is also related to other welding conditions for the steel. For instance, allowable arc heat input usually varies directly with increasing section thickness and inversely with increasing preheat temperature.

Weld thermal cycles as a function of distance from the weld centerline are shown in Fig. 5. The data presented in Fig. 5 are typical of all arc welds; the following conclusions can be drawn:

1 The peak temperature encountered decreases rapidly with increasing distance from the weld centerline.
2 The time required to reach peak temperature increases with increasing distance from the weld centerline.
3 Rates of both heating and cooling decrease with increasing distance from the weld centerline.

Similar data showing the effects of heat input and preheat are shown in Fig. 6. These data show that decreasing either the heat input or the preheat temperature results in steeper distribution of peak temperatures in the heat-affected zone. Data presented in Table 2 relate heat input and preheat temperature to time of exposure above 2000 F (to the peak temperature, 2490 F) and to cooling rate at 1200 F, which is about 100 F below the lower transformation (Ac_1) temperature. Metal in the weld zone encountering peak temperatures within this range will undergo significant changes in microstructure and mechanical properties. From the data in Table 2 it can be seen that:

1 For a given preheat temperature, increasing the heat input increases the time of exposure to temperatures above 2000 F and decreases the cooling rate at 1200 F.
2 For a given heat input, increasing the preheat temperature decreases the cooling rate at 1200 F but does not significantly influence the time of exposure to temperatures above 2000 F.

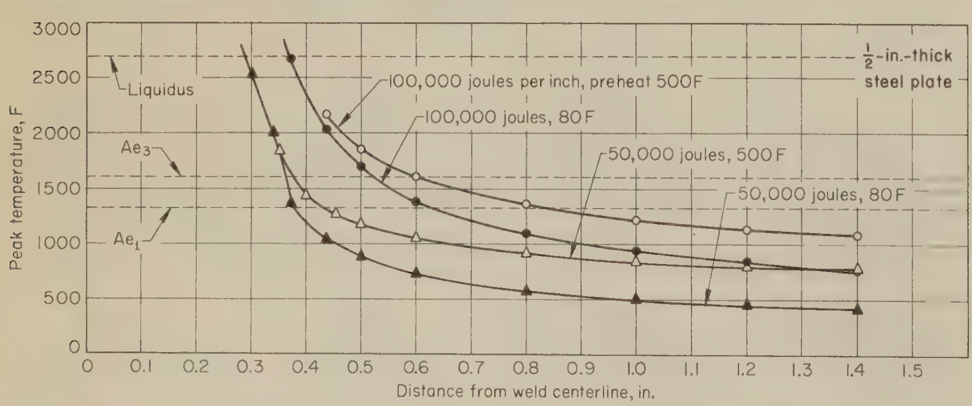
Preheating. Data in Table 2 show the significance of heat input, and of preheating, on the weld thermal cycle and, by implication, on the possibility of martensite formation. This suggests that, as an ideal precaution, all hardenable steels should be preheated to retard the cooling rate after welding. When preheating is used, section thickness, width of root face, and choice of filler metal are less critical.

Control of cooling rate (or postheating) after welding also influences the microstructure and susceptibility to cracking. With control of cooling rate (or with postheating), desired conditions are achieved by: (*a*) preventing formation of martensite by keeping the temperature of the heat-affected zone above the M_s temperature until transformation (to other products) is complete, or (*b*) decreasing the hardness of martensite by postweld tempering, if it has been allowed to form.

Multiple-pass welding may sometimes eliminate the need for preheating or postheating that would be required if the weld were made in a single pass. In multiple-pass welding, each pass serves (to some degree) as a preheat for subsequent passes and as a postheat for previous passes. Each application must be considered individually. In multiple-pass welding, the root pass is especially vulnerable to cracking when preheating is not used, particularly if the joint is highly restrained.

When preheating is not used, the usual practice is to deposit a heavy bead for the root pass. This not only imparts more heat to the joint, which results in slower cooling of the bead, but also provides greater strength and resistance to cracking of the weld metal used for the root pass.

In the example that follows, centerline cracking was eliminated without the use of preheating by changing to multiple-pass welding. In some applications, even though single-pass welds are used, if welds are close together, a similar preheating and postheating effect is obtained (see Example 216).



Data are for ½-in.-thick steel plate welded at room temperature by the manual shielded metal-arc process. (SOURCE: AWS Welding Handbook, 6th Ed., Section 1)

Fig. 6. Effect of heat input (joules per inch of weld) and preheat temperature on distribution of peak temperatures

Example 198. Change From Single-Pass to Multiple-Pass Welding To Prevent Cracking (Fig. 7)

Frames for rough-terrain trucks were fabricated from channel sections formed from ¾-in.-thick 5145 steel. Braces of ⅝-in.-thick 1018 steel were welded in each corner to stiffen the weldment, as shown in Fig. 7.

When the joints were shielded metal-arc welded in a single pass without preheat, using 3⁄16-in.-diam E7018 electrodes, at least half the welds developed cracks (Fig. 7), usually before the joints cooled.

The causes of cracking were found to be:

1 The small size of the weld deposit, and shrinkage stresses from rapid heat dissipation and cooling
2 Lack of penetration to the root of the joint
3 High restraint because of the stiffness of the members, and of the fixture holding the assembly during flat-position welding

4 High hardenability of the deposit as a result of carbon pickup from the 5145 steel base metal, which produced a hardness greater than Rockwell C 50.

Restraint and carbon pickup could not be avoided, and preheating in a furnace was not practical because of the large size of the assembly. Preheating with a torch prevented cracking in the single-pass welds, but this procedure was slow and difficult.

The problem was solved by:

1 Making each weld with three passes, to speed up welding and reduce rate of heat input and dissipation
2 Using a 5/32-in.-diam, instead of a 3/16-in.-diam, electrode for the first pass, to achieve full joint penetration (note Improved method in Fig. 7).

A conventional welding positioner was used, so that all welds could be made in the flat position. The braces were clamped to the frame corners, to avoid the need for tack welding, and all welding was done by the shielded metal-arc process, using E7018 electrodes.

The three passes were made in quick succession so that the beads could not cool appreciably between passes. Slag was quickly removed from the first bead and then the second pass was made, with a 3/16 or 7/32-in.-diam electrode. Slag was quickly removed from the second bead and the third pass was made, using an electrode of the same size as for the second pass.

The heat pattern of multiple-pass welding increased the ductility of the weld metal and heat-affected zone and reduced the hardness to Rockwell C 30 to 35.

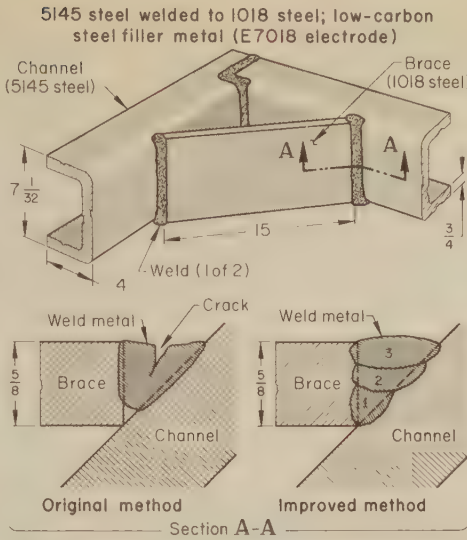


Fig. 7. Corner of a heavy-duty truck frame, showing brace that was shielded metal-arc welded without preheating. Change from single-pass to three-pass welds eliminated cracking. (Example 198)

Work-Metal Thickness. In general, the work-metal thickness influences the need for preheating. Alloy steels having relatively high hardenability often can be successfully welded without preheating when the section thickness does not exceed about ¼ in. As section thickness increases, rapid cooling by mass effect becomes more pronounced and the need for preheating increases. Concurrently, the need for higher preheating temperatures increases as section thickness increases. In the welding of thin sections when no preheat is used, even though heat dissipation is uniform and susceptibility to cracking is minimal, some hard microconstituents are likely to form. Thus, for serviceability, the weldment should usually be postheated to temper any martensite present.

On the other hand, when sections thicker than about 3 in. have been thoroughly preheated, the cooling rate after welding is so slow, because of the mass effect, that the need for postheating is minimal. For a base metal of low hardenability, postheating of heavy sections may be unnecessary.

Root Dimensions. In butt welding, the widths of the root face and of the root opening affect susceptibility to cracking, mainly because they influence the amount of welding done in the root pass. If an insufficient amount of weld metal is deposited in the root pass, the bead will lack strength, so that unless the interpass temperature is carefully maintained, cracking in the root-pass bead is likely. Angles between components being welded also influence susceptibility to weld cracking, because these angles govern the amount of weld deposit and therefore the heat input.

Shielding Gas. Regardless of the shielding gas used, its purity is more important when welding alloy steel than when welding plain carbon steel of low carbon content. A shielding gas that is made up predominantly of argon is less likely to cause cracking than is one containing predominantly carbon dioxide. The reason is that carbon dioxide permits greater heat input; consequently, penetration is deeper (see Fig. 6 on page 85 in this volume).

High-Strength Plate and Structural Steels (As-Rolled or Normalized)

Most steels of this group are known as high-strength low-alloy steels and are used extensively in construction, pressure-vessel and transportation applications. They are sold on the basis of minimum mechanical properties, primarily minimum yield strength, which is from 40,000 to 65,000 psi for the group (see Table 3).

The various producers of most of these steels have adopted different chemical compositions for steels that provide nearly identical properties. There is considerable variation in the number of alloying elements and the total alloy content. For most of the steels, total alloy content is less than 2%. The carbon content is low, usually in the range of 0.10 to 0.26%, although a carbon content as high as 0.33% is used in a few of the steels.

Weldability of these steels, a primary requirement, is somewhat less than that of carbon steels of the same carbon content. Weldability decreases as yield strength increases. However, for all practical purposes, welding of these steels is the same as welding of carbon steels that have the same carbon equivalent. As is true for other steels, weldability decreases as the thickness of the base metal increases.

Table 2. Effects of Heat Input and Preheat Temperature on Time of Exposure to Temperature Above 2000 F and on Cooling Rate at 1200 F(a)

Heat input, joules per inch	Preheat temperature, F	Time above 2000 F, to peak temperature of 2490 F, sec	Cooling rate at 1200 F, °F per sec
100,000	80	16.5	8
	500	17	2.5
50,000	80	5	25
	500	5	8

(a) Data are for heat-affected zones in ½-in.-thick steel plate arc welded using covered electrodes. (Source: same as for Fig. 5)

ASTM specifications group these structural steels according to minimum yield strength without regard to chemical composition of steels having the same mechanical properties. Table 3 lists the ASTM specifications that cover the majority of the steels, together with the minimum yield strength for each category; compositions are given in Table 4. Tables 3 and 4 cover several hundred proprietary steels.

Welding Processes. Steels covered by specifications listed in Tables 3 and 4 can be welded by any of the arc welding processes. Shielded metal-arc welding is used most often, mainly because of the nature (and very often the location) of the joints to be welded. When conditions permit, flux-cored arc, gas metal-arc, and submerged-arc welding may be used, to realize the advantages that are obtained from these processes in welding other steels. Submerged-arc welding (which can be employed only when the welding position is favorable) often proves more economical than other arc processes. Gas tungsten-arc and plasma-arc welding are seldom used for this class of steels. These processes are seldom competitive when applied to fabrication of very large structures, such as those for which these steels are generally used. Electroslag and electrogas welding have been used to a limited extent.

Filler Metals (Electrodes). Selection of a filler metal is of major importance in the welding of any alloy steel, but it becomes more critical as the hardenability of the base metal increases.

Table 3. Minimum Yield Strengths for ASTM High-Strength Plate and Structural Steels (As-Rolled or Normalized)

ASTM designation	Min YS, psi
A225, grade A	40,000
A225, grade B	43,000
A242:	
¾ in. and less(a)	50,000
Over ¾ to 1½ in.(a)	46,000
Over 1½ to 4 in.(a)	42,000
Groups 1 and 2(b)	50,000
Group 3(b)	46,000
Groups 4 and 5(b)	42,000
A299:	
1 in. and less	42,000
Over 1 to 2 in.	40,000
A302, grade A	45,000
A302, grades B, C and D	50,000
A441:	
¾ in. and less(a)	50,000
Over ¾ to 1½ in.(a)	46,000
Over 1½ to 4 in.(a)	42,000
Over 4 to 8 in.(a)	40,000
Groups 1 and 2(b)	50,000
Group 3(b)	46,000
Groups 4 and 5(b)	42,000
A572:	
Grade 42	42,000
Grade 45	45,000
Grade 50	50,000
Grade 55	55,000
Grade 60	60,000
Grade 65	65,000
A588:	
4 in. and less(a)	50,000
4 to 5 in.(a)	46,000
5 to 8 in.(a)	42,000
Groups 1 to 4(b)	50,000
Group 5(b)	46,000

(a) For bars and plates only. (b) For structural shapes; refer to ASTM A6 for details of the shapes that conform to the various groups.

Table 4. Compositions of Principal ASTM High-Strength Plate and Structural Steels Used in the As-Rolled or Normalized Condition

ASTM designation	Composition type	C	Mn	P	S	Si	Cu	Ni	Cr	Mo or Cb	V
A225, grade A	Mn-V	0.18 max	1.45 max	0.035 max	0.04 max	0.15-0.30	...	...	...	...	0.090-0.14
A225, grade B	Mn-V	0.20 max	1.45 max	0.035 max	0.04 max	0.15-0.30	...	...	...	...	0.090-0.14
A242, type 1	Mn-Cu	0.15 max	1.00 max	0.15 max	0.05 max	...	0.20 min	...	...	...	...
A242, type 2	Mn-Cu	0.20 max	1.35 max	0.04 max	0.05 max	...	0.20 min	...	...	...	...
A299:											
1 in. and less	C-Mn	0.28 max	0.90-1.40	0.035 max	0.04 max	0.15-0.30	...	...	...	...	...
Over 1 to 2 in.	C-Mn	0.31 max	0.90-1.40	0.035 max	0.04 max	0.15-0.30	...	...	...	...	...
A302, grade A:											
1 in. and less	Mn-Mo	0.20 max	0.95-1.30	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
Over 1 to 2 in.	Mn-Mo	0.23 max	0.95-1.30	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
Over 2 in.	Mn-Mo	0.25 max	0.95-1.30	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
A302, grade B:											
1 in. and less	Mn-Mo	0.20 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
Over 1 to 2 in.	Mn-Mo	0.23 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
Over 2 in.	Mn-Mo	0.25 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	...	...	0.45-0.60 Mo	...
A302, grade C:											
1 in. and less	Mn-Ni-Mo	0.20 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.40-0.70	...	0.45-0.60 Mo	...
Over 1 to 2 in.	Mn-Ni-Mo	0.23 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.40-0.70	...	0.45-0.60 Mo	...
Over 2 in.	Mn-Ni-Mo	0.25 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.40-0.70	...	0.45-0.60 Mo	...
A302, grade D:											
1 in. and less	Mn-Ni-Mo	0.20 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.70-1.00	...	0.45-0.60 Mo	...
Over 1 to 2 in.	Mn-Ni-Mo	0.23 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.70-1.00	...	0.45-0.60 Mo	...
Over 2 in.	Mn-Ni-Mo	0.25 max	1.15-1.50	0.035 max	0.04 max	0.15-0.30	...	0.70-1.00	...	0.45-0.60 Mo	...
A441	Mn-Cu-V	0.22 max	0.85-1.25	0.04 max	0.05 max	0.30 max	0.20 min	...	...	...	0.02 min
A572:											
Grade 42	Cb-V	0.21 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
Grade 45	Cb-V	0.22 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
Grade 50	Cb-V	0.23 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
Grade 55	Cb-V	0.25 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
Grade 60	Cb-V	0.26 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
Grade 65	Cb-V	0.26 max	1.35 max	0.04 max	0.05 max	0.30 max	...	...	...	0.005-0.05 Cb(a)	0.01-0.10
A588:											
Grade A	Cr-Cu-V	0.10-0.19	0.90-1.25	0.04 max	0.05 max	0.15-0.30	0.25-0.40	...	0.40-0.65	...	0.02-0.10
Grade B	Cr-Ni-Cu-V	0.10-0.20	0.75-1.25	0.04 max	0.05 max	0.15-0.30	0.20-0.40	0.25-0.50	0.40-0.70	...	0.01-0.10
Grade C	Cr-Ni-Cu-V	0.15 max	0.80-1.35	0.04 max	0.05 max	0.15-0.30	0.20-0.50	0.25-0.50	0.30-0.50	...	0.01-0.10
Grade D	Cr-Cu-Zr-Cb	0.10-0.20	0.75-1.25	0.04 max	0.05 max	0.50-0.90	0.30 max	...	0.50-0.75	0.04 max Cb(b)	...
Grade E	Ni-Cu-Mo-V	0.15 max	1.20 max	0.04 max	0.05 max	0.15-0.30	0.50-0.80	0.75-1.25	...	0.10-0.25 Mo	0.05 max
Grade F	Ni-Cu-Cr-Mo	0.10-0.20	0.50-1.00	0.04 max	0.05 max	0.30 max	0.30-1.00	0.40-1.10	0.30 max	0.10-0.20 Mo	0.01-0.10
Grade G	Ni-Cr-Cu-Mo	0.20 max	1.20 max	0.04 max	0.05 max	0.25-0.70	0.30-0.50	0.80 max	0.50-1.00	0.10 max Mo	Ti(c)
Grade H	Ni-Cu-Cr-Mo	0.20 max	1.25 max	0.035 max	0.04 max	0.25-0.75	0.20-0.35	0.30-0.60	0.10-0.25	0.15 max Mo(d)	0.02-0.10

(a) Also, 0.015 max nitrogen; for restrictions on columbium plus vanadium, and other limitations, see A572. (b) Also, 0.05 to 0.15 zirconium. (c) 0.07 max titanium. (d) Also, 0.005 to 0.030 titanium.

The strength of the weld metal deposited in the joint is the primary concern in most applications in which an alloy steel is required. Generally, therefore, filler metals must be selected that will provide the required joint efficiency, which in some cases may be less than 100%. The second major factor in selecting a filler metal is susceptibility to cracking. If the weldment is such that optimum preheating and postweld heat treatment practices can be employed, the selection of a filler metal is less critical than if welding conditions do not permit optimum (or any) preheating and postweld heat treatment.

Filler metals for arc welding of alloy steels can be classified into three general groups: (*a*) mild steels, often used when joint strength requirements are not stringent, or for joining alloy steel to mild steel; (*b*) alloy steels, used when joint strength must equal or approach that of the base metal; and (*c*) high-alloy (stainless steel or nickel-base) filler metals for special applications such as welding dissimilar steels.

Carbon content of the filler metal should never be higher than that of the base metal, because it would unnecessarily increase susceptibility to cracking. More often, the carbon content of the filler metal is lower than that of the base metal. A sufficiently close match of strength between base metal and weld metal can usually be achieved when the carbon content of the weld metal is no more than half that of the base metal.

Electrodes most commonly used for shielded metal-arc welding of high-strength plate and structural steels are listed in Table 5; low-hydrogen electrodes are recommended for all grades. Although the high-strength steels are occasionally welded with conventional electrodes, the danger of causing underbead and toe cracking is far greater with such electrodes than with low-hydrogen electrodes. The best practice for preventing such cracks, which are often difficult to detect, is to use low-hydrogen electrodes. Most regulatory codes require the use of low-hydrogen electrodes. Table 5 also shows that electrodes of higher strength and alloy content can be used as the yield strength of the steel (shown in Table 3) increases.

The moisture content of flux-covered electrodes used for welding alloy steels is an extremely critical factor in achieving sound welds. Table 6 gives the permissible maximum moisture contents for the various grades when packed in hermetically sealed containers. If these sealed containers are damaged or if for any reason there is a possibility that the electrodes have picked up moisture (see Fig. 10, and discussion on care of electrodes, on page 212), the electrodes may be restored for use by rebaking. The supplier of the electrodes should be requested to furnish proper conditions for storage and handling of electrodes, as well as times and temperatures for rebaking electrodes, so that at no time will the moisture content exceed the proper level for the electrode classification.

It is equally important to maintain low-hydrogen conditions in submerged-arc, flux-cored arc, and gas metal-arc welding, and to keep all other sources of hydrogen to required minimums. (For additional information on hydrogen, see page 212.)

Electrode wires for flux-cored arc welding of alloy steels have not been standardized. In applications permitting the use of carbon steel filler metal, alloy steels have been welded with electrodes such as E70T-1 or E70T-2, which have been standardized for the welding of carbon steels. Welds made with these filler metals in alloy steel may have lower strength than the base metal and therefore may not be acceptable for some applications.

Table 7 gives five typical compositions and as-welded mechanical properties for all-weld-metal samples from flux-cored electrodes.

Table 5. Covered Electrodes for Shielded Metal-Arc Welding of High-Strength Plate and Structural Steels (As-Rolled or Normalized)

ASTM steel	Electrode
A225, grade A	E7016, E7018
A225, grade B	E8016-C3, E8018-C3
A242	E7016, E7018
A299	E8016-C3, E8018-C3
A302:	
Grade A	E7016-A1, E7018-A1
Grade B	E8016-B2, E8018-B2
Grades C and D	E10016-D2, E10018-D2
A441	E7016, E8016-C3, E8018-C3
A572:	
Grades 42, 45	E7016, E7018
Grades 50, 55	E7016, E7018
Grades 60, 65	E8016-C3, E8018-C3
A588:	
Grade A	E7016, E7018
Grades B and C	E7016, E7018
Grades D and E	E7016, E7018
Grade F	E8016-B1, E8018-B1
Grade G	E8016-C1, E8018-C1
Grade H	E8015-G, E8018-G

Table 6. Permissible Moisture Content of Coverings on Low-Hydrogen Covered Electrodes Packaged in Sealed Containers

AWS classification(a)	Maximum moisture content, % by weight
E7015-x, E7016-x, E7018-x	0.6
E8015-x, E8016-x, E8018-x, E9015-x, E9016-x	0.4
E9018-x, E10015-x, E10016-x, E10018-x, E11015-x, E11016-x, E11018-x, E12015-x, E12016-x, E12018-x	0.2
E14018	0.1

(a) In this table, the letter suffix "-x" stands for all the suffixes listed in electrode specifications (A1, B2, C3, M, etc.).

Table 7. Typical Compositions and Mechanical Properties of Alloy Steel Weld Metal Deposited With Flux-Cored Electrodes

Electrode(a)	Composition of weld metal: C	Mn	Si	Cr	Ni	Mo	Mechanical properties(b): Tensile strength, psi	Yield strength, psi	Elongation in 2 in., %	Reduction of area, %	Recommended postheat temperature, F(c)
1	0.09	1.30	0.27	...	...	0.55	108,500	97,000	22	45	1150
2	0.05	2.00	0.40	...	2.50	0.40	123,000	108,000	14	50	1025
3	0.10	0.70	0.85	1.25	...	0.55	130,000	100,000	16	40	1250
4	0.06	0.94	0.67	2.25	...	1.0	96,000	86,000	23	60	1275
5	0.05	0.92	0.70	5.30	...	0.57	71,000	40,000	33	67	1575(d)

(a) Arbitrarily assigned numbers for identification in this table only. (b) Properties of all-weld-metal samples before postheating. (c) Time at temperature, 1 hr per inch of maximum thickness of base metal. (d) Furnace cool from 1575 F to 1100 F; then cool in air.

Table 8. AWS Classifications and Composition Limits for Mild Steel Electrodes for Submerged-Arc Welding (AWS 5.17)

AWS classification	Composition, %(a): C	Mn	Si
Carbon Steel (Low-Mn) Electrodes			
EL8	0.10 max	0.30-0.55	0.05 max
EL8K	0.10 max	0.30-0.55	0.10-0.20
EL12	0.07-0.15	0.35-0.60	0.05 max
Carbon Steel (Medium-Mn) Electrodes			
EM5K(b)	0.06 max	0.90-1.40	0.40-0.70
EM12	0.07-0.15	0.85-1.25	0.05 max
EM12K	0.07-0.15	0.85-1.25	0.15-0.35
EM13K	0.07-0.19	0.90-1.40	0.45-0.70
EM15K	0.12-0.20	0.85-1.25	0.15-0.35
2% Mn Steel Electrode			
EH14	0.10-0.18	1.75-2.25	0.05 max

(a) Electrodes of all classes also contain maximums of 0.035 S, 0.03 P, 0.15 Cu (independent of coating), 0.50 total other elements. (b) Also contains 0.05 to 0.15 Ti, 0.02 to 0.12 Zr, 0.05 to 0.15 Al — exclusive of the 0.50% content of "total other elements".

Flux-cored electrodes for depositing alloy steel weld metal are usually made by using a low-carbon steel sheath and adding the alloying elements and flux in powder form to the core. Accordingly, filler metals of special compositions can be produced economically, even in small quantities.

Low-alloy steel electrode wires such as E70T-4 are frequently used in flux-cored arc welding of high-strength structural steels, particularly the grades having yield strength up to about 50,000 psi. Electrodes such as those identified as No. 1 and 3 in Table 7, or electrodes yielding weld metal with similar composition and properties, are commonly used for welding steels of yield strength from 50,000 to 65,000 psi.

Electrode wires for gas metal-arc welding have not been standardized for alloy steels. Carbon steel electrodes such as E70S-3 are often used for welding steels having yield strength of not more than 50,000 psi, such as ASTM A242. For steels of yield strength somewhat above 50,000 psi, E70S-1B and E70S-GB electrodes have proved suitable. Structural steels of the highest yield strength (65,000 psi) can be welded with solid electrode wires having compositions similar to those of the flux-cored electrode wires No. 1 and 3 in Table 7. These, and various similar compositions, are available as proprietary compositions.

Electrode wires of the medium-manganese type, such as EM5K or EM13K (see Table 8), have proved successful for submerged-arc welding of high-strength structural steels.

Preheating. Most welding of high-strength plate and structural steels in thicknesses less than ¾ in. is done without preheating. In many applications, because of location and other welding conditions, preheating is not practical. The need for preheating, and the preheating temperatures used, depend mainly on the thickness and yield strength of the steel being welded, the type of electrode used, and required impact properties. The suggested preheating practice presented in Table 9 considers the first three of these factors and shows the advantages of using low-hydrogen electrodes. No preheating above 70 F is required for plate thickness up to 1½ in. and yield strength up to 50,000 psi when low-hydrogen electrodes are used.

The practice suggested in Table 9 generally assumes that, at the time of welding, the base metal is at least near room temperature (not colder than 50 F). If the temperature of the base metal is less than 50 F, preheating (warming) to within the range of 70 to 100 F is recommended. This is usually done with gas torches, and sometimes with strip heaters.

Even though preheating is not intended, good practice includes warming the surfaces of the work (including any joints or crevices where moisture can be entrapped) to drive off moisture, especially in humid atmospheres. Warming slightly with a torch before welding has often prevented weld porosity.

Postweld heat treating of weldments fabricated from high-strength plate and structural steels is required for some code applications, but for many it is not required.

Examples of Practice. Four applications of arc welding of high-strength plate and structural steels are described in Examples 197, 208, 212 and 219 in this article. Table 10 summarizes these examples, identifying the welding processes, base metals, filler metals, and other welding variables.

High-Strength Alloy Steels Containing up to 0.25% Carbon (Quenched and Tempered)*

The steels discussed in this section are the quenched and tempered weldable alloy steels containing not more than 0.25% carbon, and with a total content of alloying elements (not including manganese and silicon) ranging from 0.85% to about 16% (see Table 11). These steels are welded in the quenched and tempered condition and have yield strengths of 50,000 to 180,000 psi, depending on alloy content, section thickness and heat treatment. They have high strength in combination with good ductility. Various combinations of notch toughness, fatigue strength, and corrosion resistance can be developed to meet the requirements of different applications such as structures and pressure vessels for use at atmospheric, cryogenic or elevated temperatures.

*Condensed from W. D. Doty, Welding of Quenched and Tempered Alloy Steels, *Metals Engineering Quarterly*, Feb 1969, p 66-78. Example 199 has been added editorially.

Table 9. Suggested Preheating Temperatures for ASTM High-Strength Plate and Structural Steels (As-Rolled or Normalized)

Steel thickness, in.	Electrode type	Suggested preheating temperature, F, for yield strength, psi, of: 45,000	50,000	55,000	60,000	65,000
Up to ⅜	Conventional	None(a)	None(a)	None(a)	100	150
	Low-hydrogen	None(a)	None(a)	70	70	70
⅜ to ¾	Conventional	None(a)	100	150	200	250
	Low-hydrogen	None(a)	None(a)	70	70	70
¾ to 1½	Conventional	150	150	200	250	...
	Low-hydrogen	None(a)	None(a)	150	150	...
1½ to 2	Conventional	200	250	300	...	...
	Low-hydrogen	150	150	225	...	...
2 to 3	Conventional	300	300	350	...	...
	Low-hydrogen	225	225	300	...	...

(a) None means that the base metal should not be below 50 F. If it is below 50 F, it should be preheated to the range of 70 to 100 F.

Although high-strength alloy steels with up to 0.25% carbon cannot be successfully welded with simple procedures and minimal control, they are less difficult to weld than are the higher-carbon alloy steels such as 4140. The quenched and tempered alloy steels with up to 0.25% carbon were designed to be welded with moderate or no preheat, and to be used in most applications in the as-welded condition. Knowing the correct procedures that should be used for welding these steels, and rigorously following them, are fundamental to welding them successfully.

Composition, Properties and Microstructure. The composition ranges (ladle analysis) for representative high-strength alloy steels are given in Table 11. The mechanical properties of pressure-vessel-quality plates are given in Table 12. The A517 steels referred to in these tables are also produced, in accordance with ASTM A514, as structural-quality plate steels, and some are available as abrasion-resistant steel plate with minimum hardness of 321, 340 or 360 Bhn. The A543 steels, classes 1 and 2, are modifications of HY-80 and HY-100 steels, respectively. Some steels, such as A514 and A517 (grades B, F, and H), A543, HY-130, and A553, are available as heat treated shapes and seamless pipe.

A517 is a multiple-alloy boron-containing steel of 100,000-psi minimum yield strength in the heat treated condition that is now used extensively in construction equipment, bridges, buildings, pressure vessels, storage tanks, penstocks, spiral cases, and ships.

A533, grade B, steel (manganese-molybdenum-nickel steel formerly known as nickel-modified A302) has been used extensively for nuclear pressure vessels of heavy sections. The same steel at a higher strength (class 3) has been used for thin-wall pressure vessels and layered pressure vessels. A542, a 2¼Cr-1Mo steel, has been used for large-diameter hydrocracking pressure vessels that operate at elevated temperature.

The need for tough steels of high yield strength led to the development of HY-80 steel as ASTM A543. Further development resulted in HY-130, a 5Ni-Cr-Mo-V steel, and in HP 9-4-20, a 9Ni-4Co-Cr-Mo-V steel, mostly for hydrospace and aerospace requirements.

Increasing cryogenic applications led to the development of A553, grade A, a 9% Ni steel, for use at temperatures down to −320 F, and of A553, grade B, a steel of somewhat lower nickel content (8% Ni), for use at temperatures down to −275 F.

The mechanical properties given in Table 12 result from heat treatments described in Table 13.

The purpose of quenching and tempering is to produce low-temperature transformation products, such as bainite and tempered martensite, which have excellent strength combined with toughness. For example, although A533, grade B, steel has limited hardenability, the quenched and tempered microstructure in ½-in.-thick plate consists entirely of tempered martensite, which produces a tensile strength of at least 110,000 psi and a Charpy V-notch energy absorption of at least 25 ft-lb at −85 F. In a 7-in.-thick plate, the microstructure consists of ferrite and tempered bainite, and results in a tensile strength of about 90,000 psi and a Charpy V-notch

Table 10. Summary of Welding Processes, Filler Metals, and Preheating and Postheating Practices Used in Examples in This Article

Example	Welding process(a)	Base metal	Welded to	Filler metal	Temperature, F: Preheat	Temperature, F: Postheat
ASTM High-Strength Plate and Structural Steels						
208	SMAW	A441	4140	E7018	400(b)	None
212	FCAW	A572, grade 50	A36	E70T-4	70	None
197	GMAW	A242	A242	E70S-3	None	None
219	GMAW	A302, grade B	(Surfaced)	ERNiCrFe-5	None	None
ASTM High-Strength Alloy Steels (Quenched and Tempered, 0.25% C Max)						
211	SMAW	12% Mn steel	Alloy steel(c)	Stainless steel(d)	400	None
199	FCAW(e)	A514, type F	A514, type F	(f)	400(g)	1115(h)
218	GMAW	A553, grade A	A553, grade A	Inconel 625	None(j)	None
220	SAW	A333, grade 3	A333, grade 3	ER308	None	None
AISI-SAE Alloy Bar Steels						
208	SMAW	4140	A441	E7018	400(b)	None
198	SMAW	5145	1018	E7018	None	None
213	FCAW	8620	A36	(k)	400	1115
200	FCAW	4130	4130	(m)	None	Q & T
214	GMAW	4130	4130	E70S-6	None	1250(n)
217	GMAW	4140	1146	Low-carbon steel	None	None
215	GMAW	4130	4130	Low-alloy steel	None	None
221	SAW	4150	1020	EM15K	None	None
222	SAW	4027	1027	EM13K	None	None
223	SAW	4130	4140	EL12	None	900(p)
224	SAW	4130	1008 to 1025	EH14-F71(q)	None	None
225	GTAW	4140	4340	Hastelloy W	400	980 to 1000
226	GTAW	4340	4340	E70S-G	None	None
High-Strength AMS Alloy Steels (0.3 to 0.5% C)						
209	SMAW	17-22A(S)	17-22A(S)	E15016	600	1065(r)
228	GTAW	D-6ac	D-6ac	Cr-Mo steel	500 to 650	1200 to 1250
201	GTAW	D-6ac	D-6ac	D-6ac	650	900
227	GTAW	AMS 6434(s)	AMS 6428(s)	AMS 6458	400 to 500	900
202	GTAW	D-6ac	D-6ac	Low-carbon 2¼ Cr steel	500 to 650	1200 to 1250(t)
203	GTAW	D-6ac	D-6ac	17-22A(S)	400	(u)
Heat-Resisting Alloy Steels						
196	SMAW	A387, grade D(v)	Type 304	ENiCrFe-3	500(w)	1350(x)
210	SMAW	A335, grade P22(v)	Type 316	ENiCrFe-2	300(y)	1275(z)
204	FCAW	A217, grade WC9	A217, grade WC9	(aa)	450 to 600	1300
205	GMAW	H11	H11	H11	300 to 350	(bb)
216	GMAW	1.25 Cr-0.5 Mo(cc)	1.25 Cr-0.5 Mo(cc)	1.25 Cr-0.5 Mo	None	None
Tool Steels						
206	SMAW	D2	(Repair)	E312-16	700 to 900(dd)	800(ee)
207	SAW	Cr-Ni-Mo steel(ff)	(Repair)	Cr-Mo steel(gg)	750	750

(a) SMAW = shielded metal-arc welding; FCAW = flux-cored arc welding; GMAW = gas metal-arc welding; SAW = submerged-arc welding; GTAW = gas tungsten-arc welding. (b) Interpass temperature, 200 F min. (c) Similar in composition to A517. (d) Modified type 304; 0.14 max C, 4.0 to 4.5 Mn, 19 min Cr, 9 min Ni. (e) Shielded metal-arc for out-of-position welds; both processes used in shop and field welding. (f) Electrode for flux-cored arc welding had a composition of 0.15 C, 0.93 Mn, 0.22 Si, 0.75 Cr, 0.66 Ni, 0.50 Mo; for shielded metal-arc welding, electrodes had composition equivalent to E11018.

(g) Local preheat, in both shop and field. (h) Stress relief used only in shop. (j) Warmed to 70 F with torch if below 32 F. (k) An unclassified flux-cored equivalent of an E7018 flux-covered electrode. (m) As deposited, 0.15 C, 1.60 Mn, 0.55 Si, 0.70 Cr, 0.75 Mo. (n) Held at temperature for 15 min. (p) To temper martensitic structure. (q) Filler metal and flux combination. (r) For 2 hr, followed by normalizing at 1750 F for 1 hr and tempering at 1200 F for 6 hr. (s) Modified 4335. (t) For 1 hr. (u) Tempered at 600 F for 1 hr, then at 1225 to 1275 F for 2 hr.

(v) A 2.25 Cr-1 Mo steel. (w) On ferritic steel side only. (x) Entire joint heated for 1 hr. (y) Only for buttering of A335 (Cr-Mo) steel pipe; no preheat before welding of circumferential joint between the two pipes. (z) In sulfur-free atmosphere (8 hr) to temper Cr-Mo steel end.

(aa) Flux-cored wire equivalent to E9018-B3 in composition. (bb) Held at preheat temperature until placed in furnace for subsequent heat treating. (cc) A213, T11. (dd) By furnace or oxyacetylene torch. (ee) Held in furnace for 2 hr, or if oxyacetylene torch is used, weldment is then buried in lime for 12 hr. (ff) Cast steel roll containing 1.0 C, 0.9 Mn, 0.5 Si, 0.038 S, 0.038 P, 1.0 Cr, 0.5 Ni, 0.5 Mo. (gg) From a low-carbon steel tubular electrode with alloy-flux core; used with neutral flux.

energy absorption (¼-thickness location) of at least 30 ft-lb at 10 F. If the nickel, chromium, and molybdenum contents are high (as in A543 and HY-130 steels), the microstructure is tempered bainite and tempered martensite, even in very thick steel sections, and results in a desirable combination of strength and toughness. Furthermore, the HY-130 and HP 9-4-20 steels display markedly better toughness when residual or impurity elements such as phosphorus, sulfur, nitrogen, oxygen and hydrogen are restricted to the lowest possible levels.

Within carefully chosen limits on thickness, the A517 steels provide high strength and toughness with the least amount of alloying elements. The effect of quenching and tempering on the longitudinal mechanical properties of ½-in.-thick A517, grade F, steel is shown in Fig. 8. In the hot rolled condition the steel has a microstructure of proeutectoid ferrite and high-carbon martensite, which results in a yield strength of only about 80,000 psi and very poor Charpy V-notch energy absorption at −50 F. In comparison, the as-quenched microstructure contains high percentages of martensite and bainite; consequently, the yield and tensile strengths are much higher than those of the same steel in the hot rolled condition. The toughness of the as-quenched plate, although considerably better than that of the hot rolled plate, is greatly increased when the steel is tempered, particularly at temperatures above 1100 F, as shown in Fig. 8. Also, as a result of tempering, the yield and tensile strengths are significantly lowered and the tensile elongation is almost doubled.

Many studies have been made using underbead-cracking tests, fillet-weld and butt-weld restraint-cracking tests, and hot ductility tests to define the composition limits for susceptibility of steels to hot and cold cracking. Hot cracking normally occurs at a high temperature, usually just below the solidus temperature, whereas cold cracking, or delayed cracking, occurs below the M_s temperature.

Many of the quenched and tempered steels in Table 11 are usually produced with a sulfur content of less than 0.025%, and some, such as HY-130 and HP 9-4-20, are produced with a sulfur content not exceeding 0.010%. The manganese-to-sulfur ratio is generally greater than 30 to 1, so that with a carbon content of about 0.20% or less the susceptibility to hot cracking is negligible.

The A533 steel, with a somewhat higher carbon content, has negligible susceptibility to hot cracking because it has a high manganese-to-sulfur ratio, usually about 50 to 1. The A543 steel, with a low manganese content, is susceptible to cracking when the carbon content is at the maximum unless sulfur content is extremely low.

Susceptibility to cold cracking under conditions of high restraint decreases with increased M_s temperature. This effect has been attributed to the self-tempering of the martensite that forms at high temperatures within the martensite transformation range. Furthermore, cold cracking is directly proportional to the hydrogen content in the welding atmosphere.

All of the steels in Table 11 have negligible susceptibility to cold crack-

Table 11. Compositions of Representative High-Strength Alloy Steels (Quenched and Tempered)

ASTM designation	Composition type	C	Mn	Si	Ni or Cu	Cr	Mo	Other
A533, gr B(a) ...	Mn-Mo-Ni	0.25 max	1.15-1.50	0.15-0.30	0.40-0.70 Ni	...	0.45-0.60	...
A517(b):								
Grade A	Mn-Si-Cr-Mo-Zr-B	0.15-0.21	0.80-1.10	0.40-0.80	...	0.50-0.80	0.18-0.28	0.05-0.15 Zr; 0.0025 max B
Grade B	Mn-Cr-Mo-V-B	0.15-0.21	0.70-1.00	0.20-0.35	...	0.40-0.65	0.15-0.25	0.01-0.03 Ti; 0.0005-0.005 B(c)
Grade C	Mn-Mo-B	0.10-0.20	1.10-1.50	0.15-0.30	...	...	0.20-0.30	0.001-0.005 B
Grade D	Cr-Mo-Cu-Ti-B	0.13-0.20	0.40-0.70	0.20-0.35	0.20-0.40 Cu	0.85-1.20	0.15-0.25	0.04-0.10 Ti; 0.0015-0.005 B
Grade E	Cr-Mo-Cu-Ti-B	0.12-0.20	0.40-0.70	0.20-0.35	0.20-0.40 Cu	1.40-2.00	0.40-0.60	0.04-0.10 Ti; 0.0015-0.005 B
Grade F	Mn-Ni-Cr-Mo-Cu-V-B	0.10-0.20	0.60-1.00	0.15-0.35	0.70-1.00 Ni(d)	0.40-0.65	0.40-0.60	0.03-0.08 V; 0.002-0.006 B
Grade G	Mn-Si-Cr-Mo-Zr-B	0.15-0.21	0.80-1.10	0.50-0.90	...	0.50-0.90	0.40-0.60	0.05-0.15 Zr; 0.0025 max B
Grade H	Mn-Ni-Cr-Mo-V-B	0.12-0.21	0.95-1.30	0.20-0.35	0.30-0.70 Ni	0.40-0.65	0.20-0.30	0.03-0.08 V; 0.0005 min B
Grade J	Mn-Mo-B	0.12-0.21	0.45-0.70	0.20-0.35	...	...	0.50-0.65	0.001-0.005 B
Grade K	Mn-Mo-B	0.10-0.20	1.10-1.50	0.15-0.30	...	...	0.45-0.55	0.001-0.005 B
Grade L	Cr-Mo-Cu-Ti-B	0.13-0.20	0.40-0.70	0.20-0.35	0.20-0.40 Cu	1.15-1.65	0.25-0.40	0.04-0.10 Ti; 0.0015-0.005 B
Grade M	Mn-Ni-Mo-B	0.12-0.21	0.45-0.70	0.20-0.35	1.20-1.50 Ni	...	0.45-0.60	0.001-0.005 B
Grade P	Mn-Ni-Cr-Mo-B	0.12-0.21	0.45-0.70	0.20-0.35	1.20-1.50 Ni	0.85-1.20	0.45-0.60	0.001-0.005 B
A542(e)	2¼Cr-1Mo	0.15 max	0.30-0.60	0.15-0.30	...	2.00-2.50	0.90-1.10	...
A543(f)	3Ni-Cr-Mo	0.23 max	0.40 max	0.20-0.35	2.60-4.00 Ni	1.50-2.00	0.45-0.60	0.03 max V
HY-130(g)	5Ni-Cr-Mo-V	0.12 max	0.60-0.90	0.20-0.35	4.75-5.25 Ni	0.40-0.70	0.30-0.65	0.05-0.10 V
HP 9-4-20(h) ...	9Ni-4Co-Cr-Mo-V	0.17-0.23	0.20-0.30	0.10 max	8.50-9.50 Ni	0.65-0.85	0.90-1.10	4.25-4.75 Co; 0.06-0.10 V
Mod A203, gr D .	3½Ni	0.17 max	0.70 max	0.15-0.30	3.25-3.75 Ni	...	...	...
A553, grade A ..	9Ni	0.13 max	0.90 max	0.15-0.30	8.50-9.50 Ni	...	...	...
A553, grade B ..	8Ni	0.13 max	0.90 max	0.15-0.30	7.50-8.50 Ni	...	...	...
A333, grade 3 ...	3½Ni	0.19 max	0.31-0.64	0.18-0.37	3.18-3.82 Ni	...	...	...
A514, type F	Mn-Ni-Cr-Mo-Cu-V-B	0.10-0.20	0.60-1.00	0.15-0.35	0.70-1.00 Ni(d)	0.40-0.65	0.40-0.60	0.03-0.08 V; 0.002-0.006 B

NOTE. Phosphorus content is 0.035 max for all steels except HY-130 and HP 9-4-20, which contain 0.010 max P, and A333, grade 3, which contains 0.05 max P. Sulfur content is 0.040 max for all steels except HY-130 and HP 9-4-20, which contain 0.010 max S, A542, which contains 0.035 max S, and A333, grade 3, which contains 0.05 max S.

(a) See A541, class 3, and A508, class 3, for forging steels. (b) Pressure-vessel quality; see A514 for structural quality. (c) Vanadium, 0.03 to 0.08. (d) Copper, 0.15 to 0.50. (e) See A541, class 6, for forging steel. (f) See A541, class 7, and A508, class 4, for forging steels. (g) See A579, grade 12, for forging steel. (h) See A579, grade 81, for forging steel.

Table 12. Tensile Properties and Charpy V-Notch Impact Properties of Representative High-Strength Alloy Steels (Quenched and Tempered)

Steel	Composition type	Thickness range, in.	Yield strength (min or range), 1000 psi	Tensile strength (min or range), 1000 psi	Elongation in 2 in. (min), %	Charpy V-notch impact energy, ft-lb(a): Longitudinal	Transverse
A533, gr B, cl 1	MnMoNi	¼ min	50	80-100	18	30 at 10 F	...
2	MnMoNi	¼ min	70	90-115	16	30 at 10 F	...
3	MnMoNi	2 max	82.5	100-125	16	25 at −85 F(b)	...
A517, gr A, B, C, D, J and K	(See Table 11)	1¼ max	100	115-135	16	15 at −50 F	15 at −50 F
A517, gr G, H, L and M	(See Table 11)	2 max	100	115-135	16	20 at 10 F, 15 at −50 F	15 at +10 F
A517, gr E, F and P	(See Table 11)	2½ max	100	115-135	16	30 at 0 F, 20 at −50 F	20 at 0 F, 15 at −50 F
A542, class 1	2¼Cr1Mo	3/16 min	85	105-125	14	35 at 10 F	...
2	2¼Cr1Mo	3/16 min	100	115-135	13	35 at 10 F	...
A543, class 1	3NiCrMo	3/16 min	85	105-125	14	35 at 10 F	...
2	3NiCrMo	3/16 min	100	115-135	14	35 at 10 F	...
HY-130	5NiCrMoV	Less than 5/8	130-150	...	14	50 at 0 F	50 at 0 F
		5/8 to 4	130-145	...	15	50 at 0 F	50 at 0 F
HP 9-4-20	9Ni4CoCrMoV	¼ min	180	190	14	40 at RT	...
Mod A203, gr D	3½Ni	2 max(c)	65(c)	75(c)	22(c)	25 at −155 F	...
A553, gr A	9Ni	2 max	85	100-120	22	25 at −320 F	...
A553, gr B	8Ni	2 max	85	100-120	22	25 at −275 F	...

(a) The minimum required value for Charpy V-notch impact energy is subject to agreement between the steel producer and the user; the values shown here for the various steels are typical required minimums. (b) For ½-in.-thick steel. (c) Tentative.

ing, provided that suitable care is taken to limit the amount of hydrogen in the welding atmosphere.

Another feature of the steel compositions listed in Table 11 is the frequent use of molybdenum to increase resistance to tempering as well as to provide greater hardenability. Molybdenum, like the strong carbide-forming elements such as titanium, vanadium and zirconium, serves two functions: to retard softening of the steel during tempering at high temperature for increased toughness and ductility, and to provide that portion of the heat-affected zone just below the lower transformation temperature with needed resistance to excessive softening. The retarded softening of A517, grade F, steel at tempering temperatures above 900 F is illustrated in Fig. 8 by the decreased slope of the strength curves between 900 and 1100 F. Thus, in a quenched and tempered steel with adequate resistance to softening, 100% joint efficiency at the desired high strength can be readily obtained if uncommonly high heat inputs in welding are avoided. Furthermore, the resistance to tempering contributes to more uniform bendability in welded joints subjected to forming operations after welding.

Steels having excellent toughness in the unaffected base metal may have inadequate toughness in the heat-affected zone. To ensure that this does not occur, much care has been given to the composition limits and recommended welding procedures for several of the quenched and tempered alloy steels in Table 11.

The development of good notch toughness in the heat-affected zone of quenched and tempered alloy steels depends on the rapid dissipation of welding heat to permit the formation of martensite and bainite on cooling. With increasing section thickness of the steel as a plate, structural section, or forging, a higher hardenability is required to secure the desired hardened structure throughout the section. Sections 1 in. thick and greater, however, produce much higher cooling rates in the heat-affected zone during welding than do ¼-in. or ½-in. sections. Therefore, thicker sections require compositions of higher hardenability principally so that heat treatment will provide the required mechanical properties before welding, whereas thinner sections require compositions of adequate hardenability both to provide the required mechanical properties before welding and to maintain the desired properties after welding.

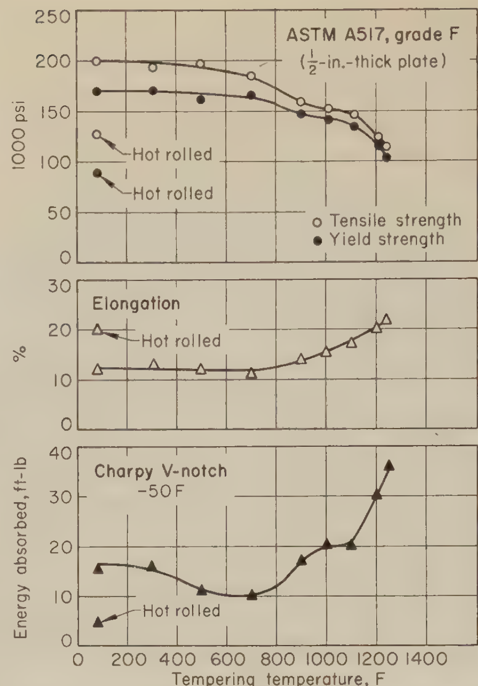


Fig. 8. Effect of quenching and tempering on the mechanical properties of ½-in.-thick ASTM A517, grade F, steel in the longitudinal direction

A microstructure produced by rapid cooling so as to have a high percentage of low-temperature transformation products (martensite and bainite) responds favorably to tempering above 1000 F, whereas the structure that results from slow cooling is only moderately improved by tempering. The structure will be comprised of upper bainite and high-carbon martensite and will have poor impact properties. These same principles apply to the microstructure produced in the heat-affected zone of a weldment.

Results of fatigue tests on butt-welded and fillet-welded joints in the weldable quenched and tempered alloy steels have shown no special sensitivity of the heat-affected zone or weld metal to fatigue failure, provided that the steel has adequate resistance to softening in the heat-affected zone, as previously discussed, and that the weld metal has adequate tensile strength. However, because fatigue-crack initiation is associated with geometric discontinuities and stress raisers, the effect of cutting and welding on fatigue must be carefully considered in relation to shape and soundness.

Location and Design of Joint. To obtain maximum advantage from the weldable quenched and tempered alloy steels, it is necessary that the increase in the yield strength of the steels be accompanied by refinements in design, workmanship and inspection. Even more thought must be given to joint design and location than with steels of which the properties are less dependent on heat treatment. A design that incorporates abrupt changes in section in a region of high stress cannot be tolerated, particularly if the steel has a yield strength of 80,000 psi or higher. Locating welds incorrectly can cause or contribute to abrupt changes in section. The welds must be located at sites where there is sufficient access for the welder and where proper examination can be made by the inspector. For these reasons, butt welds are preferable to fillet welds.

Suitable joint preparation can usually be achieved by gas or arc cutting without preheating, although some codes require preheating. For all the steels in Table 11, the steel temperature should be not lower than 50 F during cutting, but when cutting A533 and A543 steels the preheat temperature recommended for welding (see Table 15) is suggested.

Arc cutting is often preferred for steels such as A553 and HP 9-4-20. All slag or loose scale from cutting should be removed by light grinding. Prior to welding, joint surfaces should be dried, and cleaned to remove organic and hygroscopic materials. Backing bars, when required, should be made continuous, by butt welding, so as to avoid notches, which can be sites for the start of transverse cracking of weld metal. Preferably, backing bars are removed after welding in applications entailing fatigue loading. If fatigue loading is involved, the root must be inspected or back welded.

Butt joints should be welded so as to avoid creating severe stress raisers at the root. Stress raisers at this location, like those at the toe of butt or fillet welds with excessive weld reinforcement or inadequate fairing into the adjacent plates, are of greater concern when the steel has high yield strength.

Selection of the Welding Process. Shielded metal-arc, submerged-arc, flux-cored arc and gas metal-arc welding are most commonly used for joining the quenched and tempered alloy steels of carbon content up to 0.25%. These four processes can be used effectively for welding steels having yield strength up to approximately 150,000 psi. Gas tungsten-arc or electron beam welding must be used for steels of yield strength over 150,000 psi, including the HP 9-4-20 steel.

Weld cooling rates for the arc welding processes are usually so high that the mechanical properties of the heat-affected zone in the high-strength quenched and tempered steels approach those of the steel in the quench-hardened condition. Thus, postweld heat treatment, such as quenching

Table 13. Heat Treatments for Representative High-Strength Alloy Steels (Quenched and Tempered)

Steel	Treatment	Microstructure
A533, gr B	Water quenched from 1550 F (min) and tempered at 1100 F (min)	Tempered bainite and tempered martensite (thin plates); ferrite and tempered bainite (thick plates)
A517	Water quenched from 1650 F (min) and tempered at 1150 F (min)	Tempered bainite and tempered martensite
A542	Water quenched from about 1750 F and tempered at 1050 F (min)	Tempered bainite and tempered martensite
A543	Water quenched from 1650 F (min) and tempered at 1100 F (min)	Tempered bainite and tempered martensite
HY-130	Water quenched from 1475 to 1525 F and tempered at 1000 F (min)	Tempered bainite and tempered martensite
HP 9-4-20	Normalized from 1675 F, water quenched from 1550 F and tempered at 1000 F	Tempered martensite
Mod A203, gr D	Water quenched from about 1600 F and tempered at about 1100 F	Proeutectoid ferrite and fine pearlite
A553	Water quenched from 1450 to 1500 F and tempered at 1050 to 1125 F	Ferrite and austenite

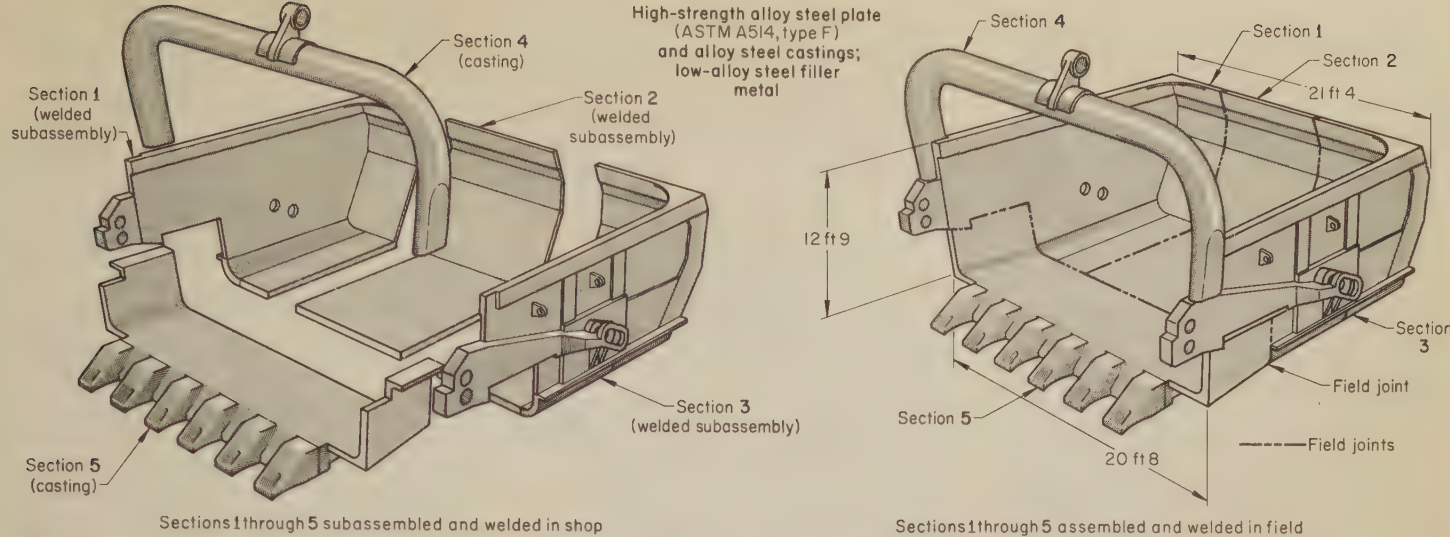


Fig. 9. Dragline bucket that, because of size and weight (158 tons), was produced as five shop-welded subassemblies that were shipped to location for field assembly and final welding. In both shop and field welding, flux-cored arc process was used for flat and horizontal positions, and shielded metal-arc for out-of-position, short, or difficult-access welds. (Example 199)

and tempering, is unnecessary unless stress corrosion is a factor. Electroslag welding, which subjects the base metal to prolonged heating and consequently slower cooling rates, generally requires quenching and tempering of these steels after welding.

Welding of structures in the field often requires welding conditions similar to those used in the shop. To minimize the problem of duplicating shop practice in the field, large sections are often fabricated in the shop and transported to the field for final assembly by welding. The example that follows describes an application in which both flux-cored arc and shielded metal-arc welding were used for joining subassemblies of 158-ton dragline buckets.

Example 199. Flux-Cored Arc Welding and Shielded Metal-Arc Welding for Assembly of 158-Ton Dragline Buckets (Fig. 9)

Because two dragline buckets, each weighing 158 tons and having a capacity of 220 cu yd, were too large to ship in one piece to the site of use, they were shop fabricated in five sections, as shown at the left in Fig. 9. Field welding of the assembled sections presented the problem of duplicating the favorable shop welding conditions.

The plate material, which was a high-strength alloy steel equivalent to ASTM A514, type F, was quenched and tempered to a tensile strength of 105,000 to 135,000 psi. Castings were of a proprietary alloy steel that had a tensile strength of 120,000 to 130,000 psi. The thickness range of the metal was from 1½ to 6 in., and the average thickness of the steel plate was about 2 in.

Groove and fillet welds were used for the various butt, corner, lap and T-joints. Welding these joints and steels required careful control of preheat and weld heat input to avoid cracking. Shop operations were as follows:

1. Plate edges were prepared by gas cutting square edges, and single and double bevels of 30° and 45°, as required.
2. Each section was assembled and tack welded.
3. The joints that were to be shop welded were preheated to 400 F by propane torches. Heat was maintained until all shop welding was completed.
4. All joints except the field joints between the five sections shown in Fig. 9 were welded using both flux-cored arc welding and shielded metal-arc welding. Flux-cored arc welding was used for welds that could be made in the flat and horizontal positions; shielded metal-arc welding, for out-of-position welds, for welds of short length, and for those that were difficult to reach. For flux-cored arc, 3/32-in.-diam electrodes were used; with larger-diameter electrode wires, welds cracked, probably because of the higher heat input and dilution effects.
   The flux-cored electrode yielded a deposit of 0.15 C, 0.93 Mn, 0.22 Si, 0.66 Ni, 0.75 Cr and 0.50 Mo. Flux-cored arc welding was done at 400 to 500 amp (dcrp) and 30 to 32 volts, using carbon dioxide (−45 F dew point, from bulk storage) at a flow rate of 30 to 35 cu ft per hour, for shielding. The electrode holder was a 600-amp water-cooled type; a 750-amp constant-voltage transformer-rectifier was used.
   Shielded metal-arc welding was done with E11018 electrodes, 5/32 and 3/16 in. in diameter, at 150 to 225 amp (dcrp) and at 20 to 30 volts.
5. To minimize distortion, long welds were made using a block sequence, in which full-size welds were deposited in the middle and at the ends of the joint and then weld beads were back-stepped to the blocks. Weld penetration was as near 100% as possible without back gouging the root bead.
6. After shop welding, the sections were stress relieved at 1115 F, furnace cooled and shipped to the site.

For field welding, the five sections were set up and cribbed in such a manner that all joints were accessible to permit welding in all positions. Because the welding had to be done in cold weather, a shelter was provided to help maintain a uniform temperature during welding. Heating was accomplished by the use of electric resistance strip heaters and large (2500 Btu) electric space heaters. Heating was maintained at all times until the job was completed, even on weekends when work stopped.

Field welding was done by the flux-cored arc and shielded metal-arc processes, under essentially the same conditions as those used in shop welding. On long welds, the block sequence described in item 5 above was used. All weld runs were completed before the next weld was started. The body plate was welded first, by joining sections 1, 2 and 3. Section 5, the lip section, was then welded to the body plate. The arch, section 4, was welded last.

Selection and Care of Electrodes. Suitable filler metals for shielded metal-arc, submerged-arc, and gas metal-arc welding of the quenched and tempered alloy steels are described in Table 14. A joint efficiency of 100% can be obtained with most steels.

The covered electrodes listed in Table 14 for joining A533, A517, A542

Table 14. Filler Metals for Joining Representative High-Strength Alloy Steels (Quenched and Tempered) by Three Welding Processes

Steel	Filler metal (and suitable flux and shielding gas, as applicable): Shielded metal-arc welding	Submerged-arc welding	Gas metal-arc welding(a)
A533, gr B, cl 1 & 2	E9018-D1	Mn-Mo wire and neutral flux	Mn-Mo wire and argon-O_2 gas
A533, gr B, cl 3	E11018-G(b) (Mn-Ni-Cr-Mo)	Mn-Ni-Cr-Mo wire and neutral flux	Mn-Ni-Cr-Mo wire and argon-O_2 gas
A517	E11018-G(b) (c) (Mn-Ni-Cr-Mo)	Mn-Ni-Cr-Mo wire and neutral flux, or carbon steel wire and alloy flux	Mn-Ni-Cr-Mo wire and argon-O_2 gas
A542, cl 1 & 2	E9015-B3	2¼Cr-1Mo wire and neutral flux	2¼Cr-1Mo wire and argon-O_2 gas
A543, cl 1 & 2	E11018-M(b)	Mn-Ni-Cr-Mo wire and neutral flux	Mn-Ni-Cr-Mo wire and argon-O_2 gas
HY-130	Special E14018 (Mn-Ni-Cr-Mo)	(d)	Special Mn-Ni-Cr-Mo wire and argon-O_2 gas
HP 9-4-20	Not recommended	Not recommended	Special Ni-Co-Cr-Mo-V filler wire with tungsten arc and argon gas
Mod A203, gr D	(e)	(e)	(e)
A553, gr A & B	68Ni-15Cr-3Ti-9Fe	65Ni-27Mo wire and neutral flux	70Ni-15Cr-3Ti-9Fe wire; helium-argon gas

(a) Consumable-electrode gas metal-arc process, except as noted for HP 9-4-20 steel, which was welded by the gas tungsten-arc process. (b) Lower-strength low-hydrogen electrodes (depending on design stress) may also be suitable. (c) A higher-strength electrode, such as E12018-G (Mn-Ni-Cr-Mo), may be necessary for thin plates of A517, grades A, B, C, D and J, steels. (d) Suitable filler metal – flux combination being developed. (e) At present, same as for A553 steel, but more economical filler metals are being developed.

and A543 steels are those commonly used, but similar low-hydrogen electrodes such as Exx15 or Exx16, with a different covering, are also suitable. Regardless of the strength of the heat treated steels listed in Table 14, electrodes that deposit weld metal having a lower strength than that of the steel are often adequate, as is true of fillet welds in longitudinal shear; in fact, lower-strength weld metal is often desirable to prevent cracking in highly restrained fillet welds.

When a carbon steel electrode and alloy-flux combination is used for submerged-arc welding, rather than an alloy steel electrode and neutral-flux combination, the welding conditions must be closely controlled, to prevent a wide variation in weld-metal composition and consequent wide variation in the cracking susceptibility and mechanical properties of the deposited metal. For example, a fabricator of components for a long-span bridge encountered cracking in submerged-arc butt welds made with a normally satisfactory combination of a carbon steel electrode wire and an alloy flux. The cracking was traced to variations in chemical composition of the weld metal, caused by fluctuations in arc voltage. Cracking was eliminated by controlling the voltage to ±1 volt, and by ensuring adequate supervision.

Hydrogen must be kept to a tolerable amount. The sources of hydrogen are:

1. Organic materials, chemically bonded water, and absorbed water in the electrode covering or welding flux
2. Hydrogen in the filler metal or in contaminants on the surface of the electrode wire, or moisture in the shielding gas or flux
3. Moisture on the steel surface at the location of welding.

In the welding of quenched and tempered alloy steels by the three metal-arc processes, hydrogen is kept to a tolerable amount in shielded metal-arc welding by using properly dried low-hydrogen electrodes; in submerged-arc welding, by using clean, dry flux and clean low-hydrogen electrode wire; and in gas metal-arc welding, by using moisture-free shielding gas and clean low-hydrogen electrode wire. For each of these processes, the steel must be dry at the location of welding. Warming with a torch is often used to ensure dry surfaces.

The low-hydrogen characteristic of covered electrodes must not be taken for granted. Normally, low-hydrogen alloy steel covered electrodes are packaged in sealed containers and the moisture content of the covering is as shown in Table 6. The coverings on special E14018 electrodes have a moisture content not greater than 0.1%. However, experience has shown that such limits on moisture content are not always sufficiently restrictive. For example, the E9015-B3 electrodes listed in Table 14 for joining A542 steels are suitable for these steels *only* if the moisture content of the covering is *less* than 0.2%, rather than the normal 0.4%. If electrodes of a lower strength class than that suggested for any particular steel in Table 14 are used, they should be baked to reduce the moisture content of the covering to that of the higher-strength electrode suggested in Table 14. For example, if E7018 electrodes, normally supplied with a maximum moisture limit of 0.6%, are to be used for welding A517 steel, the moisture content of the electrode covering should be reduced to less than 0.2%. (It should be noted that the feasibility of, and procedure for, baking depend on the composition of the electrode coating; baking should not be done without the advice of the electrode manufacturer.)

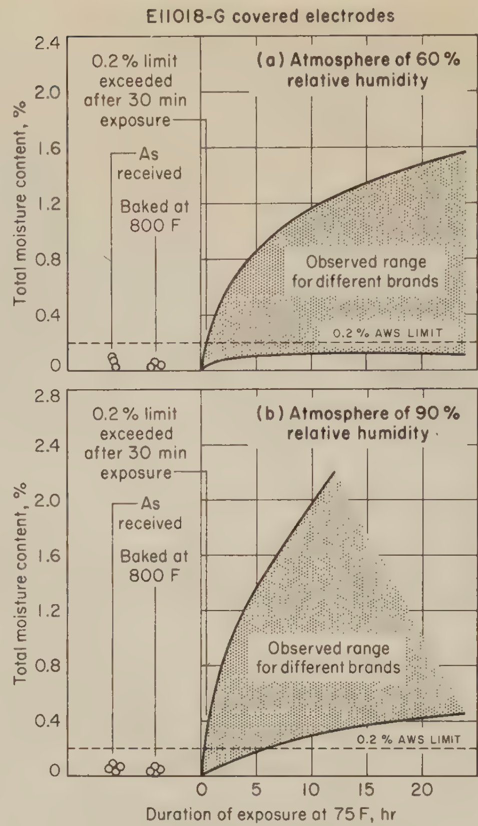


Fig. 10. Moisture content of covering on E11018-G electrodes as a function of time of exposure to atmosphere of moderate (60%) and high (90%) relative humidity

The importance of care in the storage of low-hydrogen electrodes is illustrated in Fig. 10(a) and (b), which show the effect on the moisture content of the covering on E11018-G electrodes of exposure for up to 24 hr at 75 F to atmospheres of 60% and 90% relative humidity. At both humidity levels, the permissible moisture content of 0.2% is exceeded by some of the electrodes after 30 minutes of exposure, and at 90% humidity the increase in moisture content with time of exposure is markedly accelerated.

To satisfy these rigid moisture requirements, electrodes should not be exposed to the atmosphere for more than ½ hr. Electrodes that have been exposed for longer periods must be redried before use. Failure to observe this practice is a common cause for underbead cracking in quenched and tempered alloy steel welds.

For the bare-wire electrodes used in submerged-arc, flux-cored arc or gas metal-arc welding, low hydrogen content is as important as for the covered electrodes used in shielded metal-arc welding. The total hydrogen content of bare-wire electrodes, including the hydrogen from contaminants on the wire surface, should not exceed 5 parts per million (ppm) for electrodes used to weld A517, A542 and A543 steels, and should not exceed 3 ppm for electrodes used to weld HY-130 steel. For example, transverse weld-metal cracks were noted in submerged-arc butt welds joining the flange of girders being fabricated from A517, grade F, steel for a bridge. The cracking was traced to hydrogen-producing contaminants on the surface of the bare-wire electrode used to make the welds. Cracking did not occur in similar joints made with electrode wire containing less than 5 ppm of hydrogen.

Preheating. The minimum preheat and interpass temperatures for satisfactory shielded metal-arc welds in quenched and tempered alloy steels increase with plate thickness, as shown in Table 15. Preheating is required to prevent weld-metal cracking in restrained welds, and temperature above the minimums shown in Table 15 may be required for highly restrained welds. The use of a preheating temperature of less than 100 F requires that any moisture on the plate or introduced to the arc atmosphere by the electrode or welding flux be kept to a minimum — by driving it off by mild heating, if necessary.

The maximum preheat and interpass temperatures should, in general, not exceed the minimum values given in Table 15 by more than 150 F. Otherwise, the upper limit on welding-heat input, as subsequently discussed, is very restrictive. For some grades the maximum preheat and interpass temperatures are more restrictive than for others. Thus, maximum preheat and interpass temperatures for various thicknesses of HY-130 steel plate are:

Table 15. Suggested Minimum Preheat and Interpass Temperatures When Shielded Metal-Arc Welding Representative High-Strength Alloy Steels (Quenched and Tempered)

Plate thickness, in.	Minimum preheat and interpass temperatures for welding with low-hydrogen electrodes, F: A533, B	A517	A542	A543	HY-130	Mod A203, D	A553
To ½, incl	50	50	150	100	75	50	50
Over ½ to ⅝, incl	100	50	200	125	75	50	50
Over ⅝ to ¾, incl	100	50	200	125	125	50	50
Over ¾ to ⅞, incl	100	50	200	150	125	50	50
Over ⅞ to 1, incl	100	50	200	150	200	50	50
Over 1 to 1⅜, incl	200	150	250	200	200	150	150
Over 1⅜ to 2, incl	200	150	250	200	225	150	150
Over 2	300	200	300	200	225	200	200

The minimum temperatures shown are suitable also for gas metal-arc welding and for submerged-arc welding with a neutral flux.

A preheat temperature above the minimum may be required for highly restrained welds. No welding should be done when ambient temperature is below 0 F. Steel that is at an initial temperature below 100 F may require preheating to remove moisture from its surface.

Maximum preheat and interpass temperatures should not exceed the minimums shown here by more than 150 F.

Plate ⅝ in. thick or less	150 F
Over ⅝ to ⅞ in., incl	200
Over ⅞ to 1⅜ in., incl	275
Over 1⅜ in. thick	300

The preheat and interpass temperatures suggested in Table 15 for shielded metal-arc welding are also suitable for gas metal-arc welding and for submerged-arc welding with a neutral flux. For submerged-arc welding with an alloy flux, somewhat higher temperatures are required to prevent weld-metal cracking, as shown by the preheat and interpass temperatures recommended for A517 steels in Table 16.

Heat Input and Welding Techniques. The minimum cooling rate required to produce the desired microstructures with adequate mechanical properties varies with the particular steel being welded. A cooling rate that is sufficiently high for one steel may be too low for another steel; or, expressed in terms of welding heat input, a heat input that is usable for one steel at a specific thickness and preheat may be too high for another steel under similar conditions.

Table 17 provides examples of suggested heat-input limits for some of the quenched and tempered alloy steels listed in Table 11. The limits for A533, grade B, steel in Table 17 were developed for pressure-vessel applications of class 3 steel at service temperatures down to −85 F, whereas the limits for A517, grades B, F and H, steels were developed for applications at more nearly normal service temperatures.

The heat-input limits discussed above, which were established to ensure adequate mechanical properties in the heat-affected zone, also serve to discourage the deposition of large weld beads, produced with large-diameter electrodes and high heat input, and having characteristically poor notch toughness. In welding quenched and tempered alloy steels it is good practice, whenever possible, to deposit many small beads, because this technique improves the notch toughness of the weld metal by the grain-refining and tempering action of successive passes. Such a practice is especially necessary if the welded steel is to endure severe plastic deformation, as obtains, for example, in the Navy multiple-shot explosion-bulge test performed on butt-welded specimens.

Because heat input determines the solidification characteristics and transformation structures (and consequently the properties) of the weld metal, heat input is especially important in the welding of steels of minimum yield strength greater than 100,000 psi. In Table 18, specific values of heat input are suggested for welding of HY-130 steel. Such specific conditions ensure that the heat-affected zone and the weld metal meet high strength and toughness requirements.

Stringer-bead technique, rather than weave-bead technique, is preferred in the welding of quenched and tempered alloy steels, because the heat input per inch of forward travel of the arc is lower, distortion of the joint during welding is less, and notch toughness is better in both the weld metal and the base metal. The partial weaving and uphill motion that is unavoidable when welding in the vertical position should be kept to a minimum. Air carbon-arc gouging, at a controlled heat input, followed by cleanup of the cut surface by grinding, is the preferred method for metal removal to facilitate the making of a sound weld at the root of a joint in quenched and tempered alloy steels of yield strength up to about 150,000 psi. Machining and grinding only are used for metal removal at the root of a joint in HP 9-4-20 steel.

Postweld Heat Treatment. Of the quenched and tempered alloy steels in Table 11, only A533 and A542 are usually given a postweld stress-relief heat treatment. However, these two steels have been used almost exclusively in thicknesses greater than 2 in.

Table 16. Suggested Minimum Preheat and Interpass Temperatures for ASTM A517, Grades B, F and H, Steels (a)

Plate thickness, in.	Min preheat, interpass temp, F: Shielded metal-arc or gas metal-arc	Submerged-arc: Alloy or carbon steel filler metal, neutral flux	Submerged-arc: Carbon steel filler metal, alloy flux
Up to ½, incl	50 (b)	50 (b)	50 (b)
Over ½ to 1, incl	50 (b)	50 (b)	200
Over 1 to 2, incl	150	150	300
Over 2	200	200	400

(a) Preheat temperatures above the minimums shown may be required for highly restrained welds. Maximum preheat and interpass temperatures should not exceed the minimums shown here by more than 150 F. (b) Welding of plate that is at any initial temperature below 100 F will require extreme care to minimize the formation of moisture on the steel being welded.

Table 17. Maximum Welding Heat Input in Kilojoules per Inch for Butt Welds in ASTM A533, Grade B, Steel, and ASTM A517, Grades B, F and H, Steels

Plate thickness, in.	Maximum heat input, kj/in., with preheat and interpass temperature of: 70 F	150 F	200 F	300 F	400 F
ASTM A533, Grade B, Steel					
¼	23.7	20.9	19.2	15.8	12.3
⅜	35.6	31.4	28.8	23.8	19.1
½	47.4	41.9	38.5	31.9	25.9
⅝	64.5	57.4	53.0	42.5	33.5
¾	88.6	77.4	69.9	55.7	41.9
ASTM A517, Grades B and H, Steels					
3/16	17.5	15.3	14.0	11.5	9.0
¼	23.7	20.9	19.2	15.8	12.3
⅜	35.0	30.7	28.0	23.5	18.5
½	47.4	41.9	35.5	31.9	25.9
⅝	64.5	57.4	53.0	42.5	33.5
¾	88.6	77.4	69.9	55.7	41.9
1	Any	120.0	110.3	86.0	65.6
1¼ up	Any	Any	154.0	120.0	94.0
ASTM A517, Grade F, Steel					
3/16	27.0	....	21.0	17.0	13.0
¼	36.0	....	29.0	24.0	19.0
½	70.0	....	56.0	47.0	40.0
¾	121.0	....	99.0	82.0	65.0
1	Any	....	173.0	126.0	93.0
1¼	Any	....	Any	175.0	127.0
1½	Any	....	Any	Any	165.0
2	Any	....	Any	Any	Any

$$\text{Kj/in. of weld} = \frac{\text{Amperes} \times \text{volts} \times 60}{\text{Speed, in. per min} \times 1000}$$

Heat-input limits for temperatures and plate thicknesses included, but not shown, in this table may be obtained by interpolation; 25% higher heat inputs are allowable for fillet welds.

Table 18. Suggested Welding Heat Input in Kilojoules per Inch for Joints in HY-130 Steel

Plate thickness, in.	Shielded metal-arc	Gas metal-arc
⅜ to ⅝, incl	40	35
Over ⅝ to ⅞, incl	45	40
Over ⅞ to 1⅜, incl	45	45
Over 1⅜ to 4, incl	50	50

Stress relieving is necessary for some applications in which the steel: (*a*) has inadequate notch toughness after cold forming or welding; (*b*) must retain extremely close dimensional stability during close-tolerance machining after cold forming or welding; (*c*) has high residual stresses, from cold forming or welding, that might increase susceptibility to stress corrosion. However, the need for such postweld heat treatment should be thoroughly established for each steel and application, not only because many modern steels for welded construction are designed to be used in the as-welded condition, but also because the properties of the welded steel or the weld metal joining the steel may be adversely affected by a postweld stress-relief heat treatment if stress-relieving temperature exceeds the tempering temperature. If a weldment must be stress relieved, the temperature should not exceed that used for tempering the steel. Stress-relief heat treatment at a temperature at least 50 F lower than the tempering temperature is desirable, to avoid the possibility of overtempering.

The alloying elements that contribute most significantly to the attainment of high strength and notch toughness in quenched and tempered alloy steels are usually those that have an adverse effect when such weldments are heat treated after welding.

Postweld heat treatment in the temperature range of 950 to 1200 F may impair the toughness of the weld metal and of the heat-affected zone. The extent of impairment depends on composition, heat treatment temperature, and time at temperature, and for some steels, is greater with slow cooling, as in stress relieving. Furthermore, when welds in high-strength alloy steel are given a postweld heat treatment above about 950 F, intergranular cracking may occur in the grain-coarsened region of the heat-affected zone, usually in the early stage of the stress-relief treatment. Chromium, molybdenum and vanadium contribute to this crack susceptibility. In A517, A542 and A543 steels, such stress-rupture cracking at the toes of welds has been prevented by properly contouring the welds to minimize points of abrupt change and stress concentration, by light peening at the toes of the welds, by buttering the toes of a fillet weld, or by depositing weld metal having elevated-temperature strength significantly lower than that of the heat-affected zone of the steel during the stress-relief treatment.

Suitable and serviceable welded joints in quenched and tempered steels can be ensured only by the use of welding procedures that have been prepared and tested to prove that they can consistently provide sound welds possessing the required service properties. The usual procedure-qualification tests (as in the AWS Code for Welding in Building Construction, or the ASME Boiler and Pressure Vessel Code) are generally sufficient for the majority of applications.

Examples of Practice. Four applications of arc welding of quenched and

tempered high-strength alloy steels are described in Examples 199, 211, 218 and 220 in this article. A summary of these examples, which identifies the welding processes, base metals and filler metals, and preheating and postheating practice, is presented in Table 10.

AISI-SAE Alloy Bar Steels

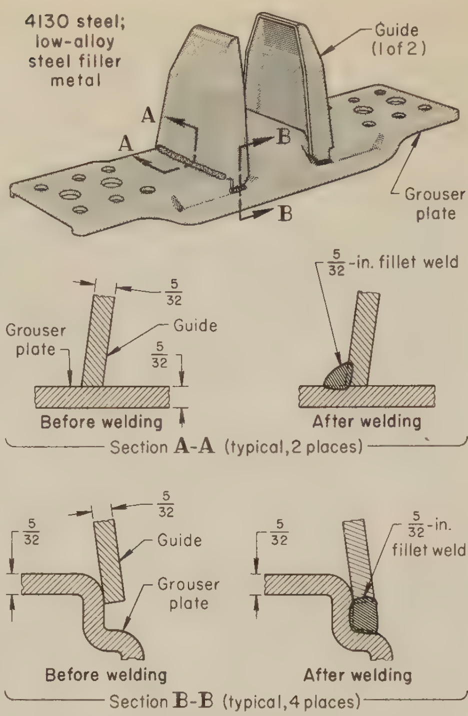
The steels dealt with in this section are the widely used hot rolled and cold finished bar steels, ranging in carbon content from 0.09 to 0.64% and in alloy content (excluding manganese and silicon) from zero (the 13*xx* series) to approximately 4.0% (the 48*xx* series). These steels are capable of developing maximum as-quenched hardness from approximately Rockwell C 36 to 65. The hardenability ranges from only slightly higher than that of plain carbon steels to that characterized by steels such as 4140H and 4340H (see Fig. 1). The weldability of these steels generally decreases as hardenability increases.

Table 19 lists 18 representative AISI alloy steels within the range of 0.18 to 0.53% carbon content. Alloy steels containing more than 0.53% carbon are seldom welded. Table 19 includes the alloy steels that are most frequently selected for weldments, with 4130 being the most widely used, because it combines high strength in the heat treated condition with acceptable weldability. The suitability of 4130 for many welding applications is indicated by the fact that it was used for at least one of the components of the weldments described in five of the 13 examples in this article that discuss the welding of alloy bar steels. Steels 4140 and 4340 are also used extensively for weldments, but are more difficult to weld without cracking than 4130 steel is.

Filler Metals (Electrodes). Table 19 lists covered electrodes commonly used for producing high-strength welds in 18 alloy steels by shielded metal-arc welding. In Table 19, E7018 (or E7018-A1, carbon-molybdenum) is shown as the choice for six steels. This electrode, a low-hydrogen, iron-powder type, provides an as-welded joint having minimum tensile strength of 70,000 psi. The minimum tensile strength, in thousands of pounds per square inch, of deposited weld metal is denoted by the first two of four, or the first three of five, digits in each electrode designation. For single-pass welds, the strength specified for the deposited weld metal usually increases as the carbon content of the base metal increases.

All of the electrodes listed in Table 19 are of the low-hydrogen type. Low-hydrogen electrodes are almost always recommended for welding alloy steels, to help prevent cracking.

Unless a joint of maximum strength is required, a lower-strength filler metal can often be used and the susceptibility to cracking thereby decreased. For instance, the electrode shown in Table 19 as commonly used for welding 4130 steel is E10016-D2, but if a lower as-welded strength is acceptable, E7018-A1 can be used. In Examples 198 and 208, E7018 was used in welding 4140 and 5145, but in both of these applications the alloy steels were welded to lower-strength steels.



Conditions for Flux-Cored Arc Welding

Joint types	T, corner
Weld type	Fillet
Welding position	Flat
Number of passes	One
Preheat	None
Postweld heat treatment	Quench and temper to Rockwell C 35 to 40
Fixture	Special, for 45° tilting
Shielding gas	Carbon dioxide, at 35 to 40 cfh
Electrode wire	5/64-in. diam(a)
Electrode holder	500 amp
Power supply	500-amp constant-voltage rectifier
Current	250 to 300 amp, dcrp
Voltage	23 to 26 v

(a) Specially formulated to produce a deposit with a composition of 0.15 C, 1.50 to 1.70 Mn, 0.50 to 0.60 Si, 0.60 to 0.80 Cr, 0.60 to 0.90 Mo.

Fig. 11. Military-tank weldment for which flux-cored electrode wire of special composition was used to meet strength requirements (Example 200)

Flux-cored electrodes are selected largely on the basis of the mechanical properties of the deposited weld metal. Because susceptibility to cracking increases as strength increases, the lower-strength filler metals should be used if the lower strength is acceptable. This kind of substitution is illustrated by Example 213, in which a lower-strength filler metal, similar to the low-hydrogen E7018, was used for joining 8620 to A36. In this application, a weld deposit with a minimum tensile strength of 70,000 psi (corresponding to the tensile strength of A36) was sufficient. For joining 4130 to 4130 in the application described in Example 200, a weld of acceptable strength was made with an electrode wire that resulted in an as-welded composition of 0.15 C, 1.60 Mn, 0.55 Si, 0.70 Cr and 0.75 Mo.

Table 19. Covered Electrodes Commonly Used for Shielded Metal-Arc Welding of Alloy Bar Steels

Steel	Electrode	Steel	Electrode
1330	E7018	4320	E7018-A1
1340	E10016-D2	4340	E12018-M
4023	E7018-A1	4620	E8016-C1
4028	E7018-A1	4640	E12018-M
4047	E10016-D2	5120	E8016-B2
4118	E7018-A1	5145	E9016-B3
4130	E10016-D2	8620	E7018-A1
4140	E12018-M	8630	E11018-M
4150	E12018-M	8640	E12018-M

Electrode wires designated as electrodes 1, 2 and 3 in Table 7 are used for welding the alloy bar steels. The one selected depends on strength requirements. Electrode No. 3 in Table 7 has been used for welding the higher-carbon steels such as 4140, 4340 and 8640 in applications where high weld strength was a requirement.

The mechanical properties of weld deposits given in Table 7 are for metal in the as-welded condition, before postheating; postweld stress relieving can result in yield and tensile strengths below the values shown, although it will frequently increase the ductility.

One advantage of the flux-cored arc process for welding alloy steels is that cored electrode wires of special composition are more readily obtained than are solid wires of special composition, as described in the following example.

Example 200. Use of Flux-Cored Wire of Special Composition To Meet Mechanical-Property Requirements in Welding 4130 Steel (Fig. 11)

In order to use the flux-cored arc welding process to achieve needed production rates, a special composition of flux-cored wire was produced to meet the mechanical properties specified for the weldment shown in Fig. 11. The weldment, part of a military tank, consisted of two guides mounted saddle-fashion on, and fillet welded to, a grouser plate.

The flux-cored electrode wire could be obtained more quickly and economically than a solid wire of special composition for gas metal-arc welding. The flux-cored wire, which was supplied in 50-lb coils, was formulated to deposit weld metal having the composition given in the table with Fig. 11. Smooth weld beads were obtained, the welds were sound, with satisfactory strength, ductility and toughness, and weld spatter was minimal.

As shown in Fig. 11, each guide required two fillet welds, which were made by the automatic method, after the assembly had been tack welded. A special fixture was used to tilt the assembly at 45° to permit welding the backs of the guides in the flat position — first one guide, then the other. The fixture was then rotated to deposit the short welds at the feet of the guides. Weld starts and stops were controlled by limit switches. After welding, the assembly was quenched and tempered to a hardness of Rockwell C 35 to 40.

Additional welding details are given in the table that accompanies Fig. 11.

Like those for flux-cored arc welding, alloy steel electrode wires for gas metal-arc welding have not been standardized. When only moderate strength is required, low-carbon steel electrodes are used (see Examples 214 and 217). When strength requirements are higher, alloy steel electrode wires that provide weld metal to match or nearly match the alloy composition of the base metal are most commonly used (Example 215). High-quality electrode wires of virtually any composition are obtainable for gas metal-arc welding. The carbon content of the electrode wire should generally be lower than that of the base metal, to minimize the formation of hard, brittle transformation products that may cause cracking. For instance, in welding 4130 steel, an electrode containing no more than about 0.20% carbon should be used. If the completed weldment is to be heat

treated (for example, quenched and tempered), a filler metal of similar composition should be used.

Table 8 lists designations and compositions of mild steel electrodes for submerged-arc welding. These electrodes are intended primarily for welding mild steel, but they are also used for alloy steel weldments, as illustrated by Examples 223 and 224. In Example 223, the low-manganese EL12 electrode was used for welding 4130 to 4140; in Example 224, the flux-electrode combination F71-EH14 (high-manganese electrode) was used to weld 4130 to 1025.

Filler metal that matches the base metal in alloy content is usually recommended when a submerged-arc weld of maximum strength is required, but the carbon content of the filler metal should be lower than (often no more than half) that of the base metal, as previously described for the gas metal-arc welding process.

In many applications, alloy steels are welded by the gas tungsten-arc process without filler metal. Selection of filler metal (if used) for gas tungsten-arc welding generally presents fewer problems than for the other arc welding processes. In gas tungsten-arc welding, the filler metal is fed into the weld puddle, not into the arc, which is an advantage because it results in more efficient alloy transfer and thus enables more accurate control over the composition of the weld metal. It is generally recommended that filler metals match the base-metal composition, but higher alloys are selected whenever special properties are needed (in Example 225, Hastelloy W was selected as the filler metal for welding 4340 to 4140 by the gas tungsten-arc process).

Preheating. Suggested preheating and interpass temperatures for 18 alloy bar steels are given in Table 20. These suggested temperatures are based on the use of low-hydrogen electrodes. The preheating temperature increases with the carbon content or hardenability of the steel and with the section thickness. If local preheating is used, the extent of preheating should be fully through the joint and for about 3 in. (or a distance equal to base-metal thickness, whichever is smaller) on either side of the joint.

The preheating temperatures suggested in Table 20 are intended as a guide. They do not take account of the interrelated variables. The interrelation of variables sometimes eliminates or minimizes the need for preheating alloy steels that have relatively low hardenability. The carbon-equivalent formula given on page 200 in this article can be used as a guide.

Alloy steels can be welded successfully without preheating, as is substantiated by the fact that preheating was used in only three of the 13 examples in this article that deal with welding of alloy bar steels (see Table 10). In the applications where no preheating was used, an examination of the example in detail reveals at least one reason for its omission. For instance, in Example 198 the welding technique was modified in order to eliminate cracking and the need for preheating. Often, preheating of the entire weldment is impractical, so that if preheating is needed, it must be done locally. Preheating is costly in all applications.

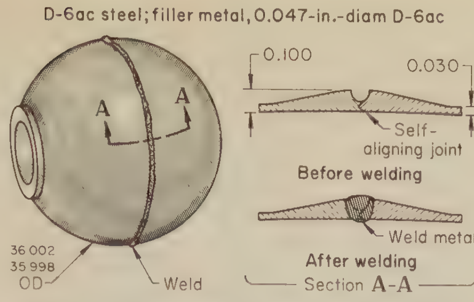


Fig. 12. Rocket-motor case gas tungsten-arc welded from two spun hemispheres that had been quenched and tempered before welding (Example 201)

Postheating. Generally, postheating is specified for the steels in Table 20 that contain more than about 0.35% carbon, although there are many exceptions (see Table 10). One practice for welding these higher-carbon steels is to use a preheating and interpass temperature that is just above the M_s temperature for the particular steel, and then to hold at this temperature for at least 1 hr. The objective is to permit the weld metal to transform from austenite to softer microconstituents, rather than to martensite, and thereby to minimize the possibility of cracking without undue sacrifice in mechanical properties.

Stress relieving is usually required and may be mandatory for weldments of all of the steels listed in Table 20, if the weldment is to be put into service without being quenched and tempered, but if a weldment is to be quenched and tempered, stress relieving can usually be omitted. Dimensional stability and notch toughness usually determine the need for stress relief.

In preferred practice, the heating for stress relieving, or for the austenitizing that precedes quenching, should begin before the weldment cools to a temperature below the interpass temperature. However, this procedure is not always practical, and in some applications the weldment remains at room temperature for an indefinite time before being stress relieved. Drafts of air impinging on the weldment while it is cooling to room temperature should be avoided.

For complete, or almost complete, stress relief, the weldment should be heated to 1100 to 1250 F and held for one hour per inch of maximum base-metal thickness. If heating in this range is impractical, partial stress relief can be attained by heating at a lower temperature (for instance, 900 F) for several hours.

Examples of Practice. Thirteen examples in this article describe applications of arc welding of alloy bar steels; Table 10 identifies the welding processes, base metals and filler metals, and preheating and postheating practice (when such practice was employed).

Table 20. Suggested Preheat and Interpass Temperatures for Various Alloy Bar Steels

Steel	Preheat and interpass temperature, F, for section thickness of: To ½ in.	½ to 1 in.	1 to 2 in.
1330	350-450	400-500	450-550
1340	400-500	500-600	600-700
4023	100 min	200-300	250-350
4028	200-300	250-350	400-500
4047	400-500	450-550	500-600
4118	200-300	350-450	400-500
4130	300-400	400-500	450-550
4140	400-500	600-700	600-700
4150	600-700	600-700	600-700
4320	200-300	350-450	400-500
4340	600-700	600-700	600-700
4620	100 min	200-300	250-350
4640	350-450	400-500	450-550
5120	100 min	200-300	250-350
5145	400-500	450-550	500-600
8620	100 min	200-300	250-350
8630	200-300	250-350	400-500
8640	350-450	400-500	450-550

High-Strength AMS Alloy Steels Containing 0.30 to 0.50% Carbon

The steels of this group have carbon content in the range of 0.30 to 0.50%, and total content of chromium, nickel, molybdenum and vanadium between approximately 2.0 and 7.0%. These alloy steels have high hardenability and, depending primarily on their carbon content, may be capable of developing high hardness and may prove difficult to weld without cracking.

Representative compositions are given in Table 21. Although some compositions are closely similar to those of the AISI-SAE alloy bar steels (4340, for example), they are always purchased to AMS (Aerospace Material Specifications) requirements, and the principal field of application for these steels is in the aerospace industry. They are sometimes welded in the quenched and tempered condition; generally, however, welding is done before final heat treatment. In nearly all applications, a postweld heat treatment is required.

The next example describes production of a rocket-motor case by welding together two hemispheres of D-6ac steel in the heat treated condition.

Example 201. Welding High-Strength Alloy Steel Rocket-Motor Cases in the Heat Treated Condition (Fig. 12)

Special design and preheat and postheat techniques made it possible to weld D-6ac rocket-motor cases in the quenched and tempered, rather than in the annealed, condition. As shown in Fig. 12, the motor cases consisted of two 36-in.-diam, 0.030-in.-wall spun hemispheres welded at the equator. Heat treated D-6ac was used in this application to provide a minimum yield strength of 200,000 psi. Manufacturing the motor cases by welding before quenching and tempering would have been difficult, if not impossible, because of the need to maintain a ±0.002-in. tolerance on the diameter.

Wall thickness at the joint was increased to 0.100 in. to compensate for expected decrease in strength due to the welding heat. Because a slight mismatch at the joint could cause loss of tolerance and reduce

Table 21. Nominal Compositions of Some High-Strength AMS Alloy Steels Containing 0.30 to 0.50% Carbon

AMS No.	Similar to	C	Mn	Si	Cr	Ni	Mo	V
6302, 6385	17-22A(S)	0.30	0.55	0.65	1.25	...	0.50	0.25
6415	4340	0.40	0.75	0.27	0.80	1.80	0.25	...
6428, 6434	4335 mod	0.35	0.72	0.27	0.80	1.80	0.35	0.20
6431	D-6ac	0.47	0.75	0.22	1.05	0.55	1.00	0.11

strength, a self-aligning type of joint was used (see Fig. 12).

To avoid the development of a brittle heat-affected zone, the joint was locally preheated to 650 F, and held at that temperature during welding and for 1 hr thereafter. Then the welded joint only was locally stress relieved at 900 F for 1 hr, using radiant heating equipment. The resulting structure was strong and ductile enough to meet specification requirements.

Equipment consisted of a gas tungsten-arc stationary head with automatic voltage control. The workpiece was rotated beneath the arc on a circumferential fixture supplied with electrically heated hold-down and backup tools made of stainless steel. Welding conditions were generally the same as in Example 227 (see table, Fig. 35).

Welding Processes. Shielded metal-arc and gas metal-arc welding have been used successfully for joining these steels (Example 209 describes an application of shielded metal-arc welding), but gas tungsten-arc welding is generally preferred and more often used, because it provides more precise control. Plasma-arc welding and electron beam welding have also been used successfully (see Table 7 on page 143 in the article on Plasma-Arc Welding for typical conditions for plasma-arc welding of D-6ac steel, and the article on Electron Beam Welding, which begins on page 519).

Susceptibility to Cracking. With the exception of some high-carbon tool steels, these AMS alloy steels, as a group, are the most susceptible of all steels to the various types of weld cracking. Of the steels for which compositions are given in Table 21, AMS 6431 (well-known as D-6ac) is the most susceptible to cracking, because it has the highest carbon content. However, the demand for AMS 6431 for components such as motor cases, missile tanks and other aerospace hardware has resulted in the development of welding techniques that produce acceptable results.

Gas Tungsten-Arc Welding of D-6ac. The welding and heat treating procedures described in the remainder of this section (including Examples 202 and 203) are from the article "Weldability of Low-Alloy Steels Heat Treated After Welding", by D. K. Hanink and N. F. Bratkovich, *Metals Engineering Quarterly*, Feb 1969, p 18-27.

Base Metal and Preweld Heat Treatment. The earliest high-strength rocket-motor cases and missile tanks were fabricated from alloy steels such as 4130 and 4340. Because of low fracture toughness, resulting from attempting to achieve yield strengths above 200,000 psi, these steels proved unsatisfactory. To obtain the required high yield strength, the quenched steels had to be tempered in the range of 500 to 700 F. In addition to the low fracture toughness, these low tempering temperatures did not allow temper straightening of large pressure vessels, which distort during welding and heat treating.

These difficulties led to the development and use of secondary-hardening, low-alloy martensitic steels, such as D-6ac, that can be tempered in the range of 1000 to 1125 F to provide a combination of high yield strength and good fracture toughness.

Steel D-6ac, procured to AMS 6431 (vacuum melted from consumable electrodes), is used for pressure-vessel applications utilizing gas tungsten-arc welding. Most of these pressure vessels are tempered at 1000 F. Large thick-wall vessels, however, require slightly higher tempering temperatures (in the range of 1000 to 1125 F).

Depending on the specific application, the D-6ac steel to be welded was obtained as machined rolled rings or as cylinders spun from premachined forged rings. Heat treatment for original forgings was a normalizing treatment at 1750 F, air cooling, then tempering at 1300 F for 4 hr and air cooling. Stress relieving at 1300 F for 1 hr sometimes followed rough machining. A heat treatment at 1650 F plus a 1300 F temper was used after spinning and before final sizing. The sized cylinders were trimmed and the ends were machined and abrasive blast cleaned for welding.

Table 22. Compositions of Filler Metals Used for Gas Tungsten-Arc Welding of D-6ac Alloy Steel(a)

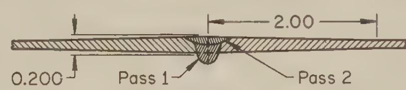
Element	2.25% Cr(b)	17-22A(S)(c) (AMS 6458)
Carbon	0.08-0.14	0.28-0.33
Manganese	0.40-0.70	0.45-0.65
Silicon	0.30-0.55	0.55-0.75
Phosphorus	0.008 (max)	0.008 (max)
Sulfur	0.008 (max)	0.008 (max)
Chromium	2.25-2.75	1.15-1.35
Molybdenum	0.85-1.10	0.40-0.60
Vanadium	...	0.20-0.40
Oxygen	0.0025 (max)	0.0025 (max)
Hydrogen	0.0025 (max)	0.0025 (max)
Nitrogen	0.005 (max)	0.005 (max)

(a) Filler-metal wires were drawn from vacuum-melted stock and had a mirror-finish surface. (b) For joint thickness of about 0.200 in. (c) For joint thickness of about 0.900 in.

Table 23. Gas Tungsten-Arc Welding Procedure for 0.200-In.-Thick D-6ac Steel (Example 202)

Preheat .... 500 to 650 F
Postheat (1 hr) .... 1200 to 1250 F
Filler wire .... 0.060-in.-diam 2¼ Cr(a)

	Pass 1	Pass 2
Filler-wire feed, ipm	...	20 to 35
Current, amp	150 to 220	150 to 220
Voltage	9 to 11	9 to 11
Welding speed, ipm	4½	4½
Torch gas, cfh	5 A, 35 He	35 argon
Trailing gas, cfh	20 argon	20 argon
Backing gas, cfh	25 argon	25 argon

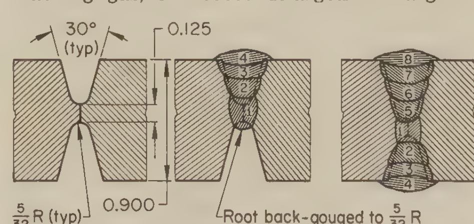


(a) See Table 22 for composition.

Table 24. Gas Tungsten-Arc Welding Procedure for 0.900-In.-Thick D-6ac Steel (Example 203)

Preheat .... 400 F
First temper (1 hr) .... 600 F
Second temper (2 hr) .... 1225 to 1275 F
Filler wire .... 0.060-in.-diam 17-22A(S)(a)

	Passes 1-4	Passes 5-8
Filler-wire feed, ipm	29 to 38	20 to 38
Current, amp	250 to 280	275 to 300
Voltage	12 to 14	12 to 14
Welding speed, ipm	3	3
Torch gas, cfh	10 A, 30 He	30 A, 10 He
Trailing gas, cfh	40 argon	40 argon
Backing gas, cfh	40 argon	40 argon



(a) See Table 22 for composition.

Filler Metal. Criticality in the choice of filler metal for good fracture toughness in D-6ac weldments was minimized when the base metal was tempered at temperatures higher than 1000 F. Because cracking of weld deposits and low ductility of the welded joints resulted when the filler metal matched the composition of the D-6ac base metal, modified low-alloy filler metal with carbon content somewhat lower than that of the base metal was used. Correct joint preparation and control of heat input in welding were important in maintaining consistent dilution of weld metal by base metal.

For joint thicknesses of about 0.200 in., a low-carbon, 2¼% chromium alloy steel filler metal was used to produce a weld in which considerable base-metal dilution was achieved. For joint thicknesses of about 0.900 in., a higher-carbon, lower-alloy filler metal was used, because there was less dilution in the larger welds. Carbon and alloy contents of the filler metal were adjusted to obtain satisfactory response to heat treatment. The compositions of the two filler metals are given in Table 22.

Welding Procedure. When welding a medium-carbon, low-alloy steel of this type, good results were obtained when preweld and postweld heat treatments were employed to control weld cooling rates so as to produce mixed structures of bainite and tempered martensite in the weld zone and to prevent the formation of primary martensite. Such structures could better withstand subsequent processing and final heat treatment to produce high weld joint efficiency and high notch toughness.

Examples 202 and 203. Procedures for Welding D-6ac Steel 0.200 and 0.900 In. Thick (Tables 23 and 24)

The details of a procedure for girth welding of a 0.200-in.-thick pressure vessel (Example 202) are shown and described in Table 23. The girth welds were made in two passes by automatic gas tungsten-arc welding. To maintain the required preheat and interpass temperatures, resistance heating elements were incorporated in backup supporting ID and OD rings. Appropriate grooves in the backup support rings provided for adequate shielding of the weld joint by inert gas. On completion of the welding operation, induction heating was used for the postweld stress relieving.

The detailed welding procedure for joining 0.900-in.-thick D-6ac steel (Example 203) is given in Table 24. Considerably greater restraint was encountered in the thick-wall pressure vessel, and eight passes were required in welding the double-U joint. The automatic welding machines that were used incorporated a closed-circuit TV system to monitor deposition of the ID weld passes. A combination of local induction heating and furnace heat treatment was essential in postweld stress relief.

The welding, postweld heat treatment, and semifinishing of weld face and root were sequenced to accommodate nondestructive testing. If weld repair was necessary, the procedures were similar to those used for the production operation, but manual gas tungsten-arc welding was used for minor weld repairs.

Final Heat Treatment. Before final heat treatment, the pressure-vessel weldments were thoroughly inspected for soundness and the existence of any

undesirable sharp weld undercut that could be a source from which a quenching crack might start during the hardening operation. The final heat treatment was:

1 **Austenitize.** 1650 F for 1 hr, hot salt quench at 400 F for 10 min, air cool.
2 **First Temper.** 400 F for 1 hr, air cool.
3 **Final Temper.** Thin-wall (0.200-in.) vessels: 1000 F for 4 hr, air cool. Thick-wall (0.900-in.) vessels: 1125 F for 4 hr, air cool.

In the final tempering operation, ring fixtures for rounding and straightening were used to hold dimensions within the required limits. Control samples, selectively positioned on the vessel, were used to measure response to heat treatment and mechanical properties.

The weldment (weld area and adjacent base metal) was thoroughly inspected after final heat treatment, prior to final machining and hydrostatic testing.

Examples of Practice. Table 10 summarizes six examples in this article that describe applications of arc welding of high-strength AMS alloy steels. In addition, Example 205 (next page) describes fabrication of rocket-motor cases from H11 tool steel, a 5% Cr, 1.5% Mo steel widely used in aerospace structural applications (AMS 6437).

Heat-Resisting Alloy Steels

The ten heat-resisting steels of which the nominal compositions are given in Table 25 are typical of the alloy steels used for components of boilers, petroleum-refining equipment, and other products that operate at elevated temperatures up to about 1050 F. They have a total alloy content (chromium, molybdenum and vanadium) in the range of 0.5 to 10%.

The six grades of ASTM A335 steel listed in Table 25 are used for seamless alloy steel pipe. The alloy content of the six steels varies from 0.5 to 10%, and with the exception of grade P1 their carbon content is 0.15% max. They are specified to be in a formable condition as purchased, either fully annealed or, more often, quenched and tempered, or normalized and tempered (they are tempered at about 1250 F).

A193, grade B16, is designed for high-temperature bolting applications. It is available as bars or forgings in various conditions of heat treatment.

AISI 501 and 502 have the same composition except for carbon content. They are available in various product forms and several conditions of heat treatment and are used in a wide variety of elevated-temperature applications such as oil-refinery equipment.

H11 is primarily a hot work tool and die steel but it is also used in structural applications that require high strength at elevated temperature.

Welding Processes. Of the five examples in this article that deal with arc welding of heat-resisting alloy steels (see Table 10 for a directory and summary), two involve the use of shielded metal-arc welding, in two others the process was gas metal-arc welding, and in one the flux-cored arc process was used. In addition to these three arc welding processes, submerged-arc welding also has been used successfully and has the same capabilities and limitations for heat-resisting alloy steels as for other types of alloy steels.

For the pipe and bolt grades, gas tungsten-arc welding is seldom used for making the entire weld, although it is sometimes used for making the root pass in the welding of pipe sections. This can be done with or without filler metal; consumable inserts are often used (see page 128 in Gas Tungsten-Arc Welding). The filler passes are then made by either the shielded metal-arc or the gas metal-arc process.

The gas tungsten-arc process is often used for welding H11, 501 and 502 when close control of the weld composition is required.

The two examples that follow compare alternative welding processes used for welding of heat-resisting alloy steels. The first example illustrates why flux-cored arc welding was preferred to shielded metal-arc welding for repair of alloy steel castings conforming to ASTM A217, grade WC9. The second example describes an application in which welding time was reduced by as much as 87% by a change from the automatic gas tungsten-arc to the automatic gas metal-arc process for welding of H11 steel motor cases.

Example 204. Cost of Repairing Heat-Resisting Alloy Castings by Shielded Metal-Arc vs Flux-Cored Arc Welding (Table 26)

The use of shielded metal-arc welding to repair defects in large heat-resisting alloy steel castings for pressure service was found to be slow and costly for the large volume of work involved. Some of the cavities that had to be filled required 60 lb of weld metal. Of the several available alternative processes, flux-cored arc welding with auxiliary gas (carbon dioxide) shielding was favored.

Welding costs for shielded metal-arc welding were known. Therefore, a cost study was made of the flux-cored arc process for repairing defects in alloy steel castings conforming to ASTM A217, grade WC9 (0.18% C, 2.5% Cr, 1.0% Mo). A typical casting measured 4 by 6 by 8 ft over-all, weighed approximately 14,000 lb and was valued at about $18,000. The welds were made in accordance with the repair requirements of the specification, which applied equally to all welding processes.

Operations such as preparing the defect cavity for welding, preheating, control of interpass temperature, postweld stress relief, qualification details, inspection and testing were the same for both processes. Reference radiographs of ASTM E71, class 3, were used as the acceptance criteria for the control of weld quality. It was possible, therefore, to compare costs strictly on the basis of the welding operation.

Welding conditions for both processes are given in Table 26. Control of preheat and interpass temperatures, and the use of postweld stress relief, were important in helping to minimize cracking and dimensional instability in welding this alloy steel. The flux-cored electrode used for this application was supplied as being equivalent to the E9018-B3 iron-powder, low-hydrogen electrode used for shielded metal-arc welding. Weld deposits having a nominal composition of 0.12% C, 2.5% Cr and 1.0% Mo approximately matched the composition of the base metal (0.18% C, 2.5% Cr, 1.0% Mo). The 90,000-psi minimum tensile strength of the weld metal was considerably higher than the minimum tensile

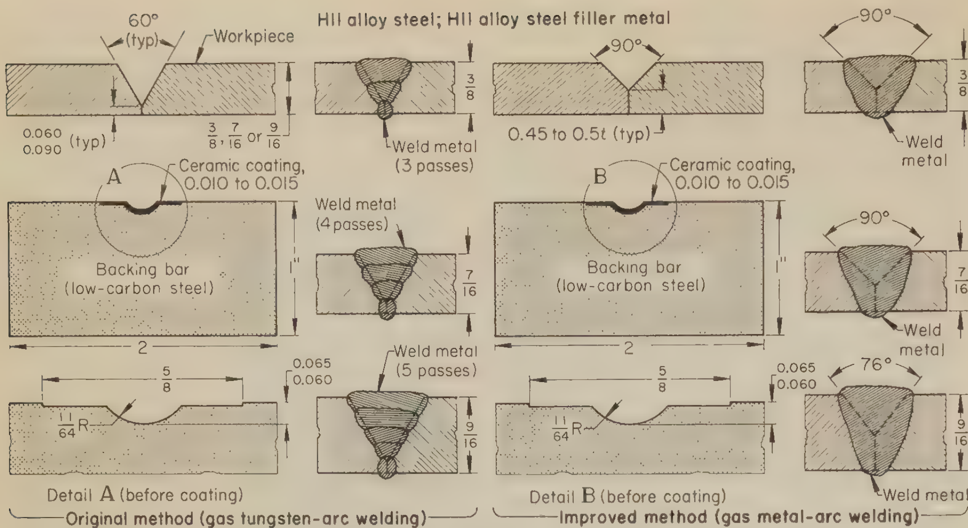
Table 25. Nominal Compositions of Typical Wrought Heat-Resisting Alloy Steels

Steel	C	Mn	Si	Cr	Mo	V
ASTM A335, grade P1	0.10 to 0.20	0.55	0.30	...	0.5	...
grade P12	0.15 max	0.45	0.50 max	1.0	0.5	...
grade P11	0.15 max	0.45	0.75	1.25	0.5	...
grade P22	0.15 max	0.45	0.50 max	2.25	1.0	...
grade P7	0.15 max	0.45	0.75	7.0	0.5	...
grade P9	0.15 max	0.45	0.62	9.0	1.0	...
ASTM A193, grade B16	0.40	0.60	0.27	1.0	0.55	0.30
AISI 501	0.10 min	1.0 max	1.0 max	5.0	0.5	...
AISI 502	0.10 max	1.0 max	1.0 max	5.0	0.5	...
H11 tool steel (AMS 6437)	0.35	...	...	5.0	1.5	0.40

Table 26. Welding Conditions and Comparison of Costs for Repairing a Casting Defect by Shielded Metal-Arc and Gas-Shielded Flux-Cored Arc Welding (Example 204) (a)

Item	Shielded metal-arc	Flux-cored arc
Welding Conditions		
Electrode	¼-in.-diam E9018-B3	3⁄32-in.-diam (b)
Welding position	Flat ± 30°	Flat ± 30°
Current	310 to 420 amp, dcrp	400 to 500 amp, dcrp (c)
Voltage	23 to 27 v	30 to 33 v
Gas shielding	None	CO_2 at 40 to 50 cfh
Power supply	500-amp rectifier	600-amp rectifier
Preheat	450 F	450 F
Interpass temperature	450 to 600 F	450 to 600 F
Postheat	1300 F stress relief	1300 F stress relief
Cost Comparison		
(A) Electrode cost per pound	$0.47	$0.545
(B) Electrode deposition efficiency (d)	65%	88%
(C) Electrode cost per pound of weld deposit (A/B)	$0.72	$0.62
(D) Shielding-gas cost per pound of weld deposit	None	$0.03
(E) Electrode deposition per arc-hour	8.5 lb	16 lb
(F) Arc-time duty cycle (e)	25%	40%
(G) Electrode deposition per labor-hour (E×F)	2.13 lb	6.4 lb
(H) Labor and overhead cost per hour	$9.00	$9.00
(I) Labor and overhead cost per pound of weld deposit (H/G)	$4.23	$1.41
(J) Total cost per pound of weld deposit (I+C+D)	$4.95	$2.06

(a) Alloy steel casting A217, grade WC9 (0.18% C, 2.5% Cr, 1.0% Mo). (b) Weld-metal deposit equivalent to that of E9018-B3 covered electrode. (c) A 1½-in. stickout was used. (d) Pounds of weld metal deposited per pound of electrode consumed, expressed as a percentage. (e) Arc-hours per labor-hour, as a percentage.



Item	Gas tungsten-arc welding	Gas metal-arc welding
Welding position	Flat	Flat
Number of passes	Three, four or five(a)	One
Preheat	300 to 350 F	300 to 350 F
Postheat	Stress relieve while at preheat	Stress relieve while at preheat
Filler metal	1/16-in.-diam H11 wire(b)	3/32-in.-diam H11 wire
Electrode	3/32-in.-diam EWTh-2, tapered	See filler metal above
Electrode extension	3/8 in. beyond cup	5/8 to 3/4 in.
Shielding gas	Argon(c)	98% argon – 2% oxygen(c)
Wire-feed rate	20 to 42 in. per minute	Current-regulated feed
Power supply	750-amp transformer	750-amp constant-voltage rectifier
Current	70 to 135 amp, ac(d)	460 to 470 amp, dcrp
Voltage	10 to 14 v(e)	30.4 to 30.6 v
Arc stabilization	High frequency	None
Travel speed	8 to 11 in. per minute (avg)	13 in. per minute (avg)
Welding time:		
Longitudinal welds	132 min (for 9/16-in. thickness)	11 min (for all three thicknesses)
Two circumferential welds	522 min (for 9/16-in. thickness)	76 min (for all three thicknesses)
Total welding time(f)	6.8 to 11.4 hr(g)	1.45 hr (for all three thicknesses)

(a) Depending on base-metal thickness, as shown in illustration; root pass for each thickness was made without filler metal. (b) Except for root passes, which were made without filler metal. (c) No trailing shield was used for gas tungsten-arc welding, and with a ceramic-insulated backing bar, no backing gas was needed; no backing gas was required for gas metal-arc welding. Before welding, electrode holder and joint were purged with shielding gas for 15 to 30 sec, at a flow of 15 cu ft per hour. (d) First pass, 70 amp; second pass, 95 amp; third pass, 110 amp; fourth pass (7/16-in. thickness), 135 amp; fourth and fifth passes (9/16-in. thickness), 135 amp. (e) First pass, 10.5 volts; remaining passes, 10 to 14 volts. (f) Includes one 10-ft longitudinal weld and two 10-ft-diam circumferential welds. (g) For thicknesses of 3/8 to 9/16 in.

Fig. 13. Designs of longitudinal and circumferential joints in 10-ft-diam, 10-ft-long rocket-motor cases for which process was changed from multiple-pass gas tungsten-arc welding to single-pass gas metal-arc welding, effecting a 79 to 87% saving in welding time (Example 205)

strength of the base metal (70,000 psi), established by ASTM A217.

The cost comparison is summarized in Table 26, in terms of cost per pound of weld deposit. Because a pound of weld metal deposited by flux-cored arc welding cost less than half that of weld metal deposited by the shielded metal-arc process, flux-cored arc welding was adopted by the foundry for all possible casting repairs.

Example 205. Change From Gas Tungsten-Arc to Gas Metal-Arc Welding of H11 Steel Rocket-Motor Cases To Reduce Welding Time (Fig. 13)

Automatic gas tungsten-arc welding of H11 steel rocket-motor cases produced high-quality joints, but the process proved too costly because of the long welding time it required. As a result of extensive laboratory tests, a procedure for automatic gas metal-arc welding was developed which reduced welding time by approximately 79% for 3/8-in.-thick plates to 87% for 9/16-in.-thick plates.

The two welding procedures were compared on the basis of welding a longitudinal joint and two circumferential joints of a cylinder 10 ft in diameter and 10 ft long, in three thicknesses: 3/8, 7/16 and 9/16 in. Because H11 steel is air-hardening, precise temperature control during welding was essential.

Joint configurations and welding conditions for the two processes are given in Fig. 13 and the companion table. Automatic equipment and tooling were essentially the same for both processes. Longitudinal welds were made on a conventional seam welder, and girth welds were made in a fixtured positioner.

As shown in Fig. 13, the gas tungsten-arc welds were made in three passes for the 3/8-in. thickness, four passes for the 7/16-in., and five for the 9/16-in. For all three thicknesses, the root pass was made without filler metal. Average total welding time for the three gas tungsten-arc welded joints ranged from 6.8 hr for the 3/8-in. thickness to 11.4 hr for the 9/16-in. thickness.

The gas metal-arc welds in all three thicknesses were deposited in single passes, which enabled three joints to be welded in an average total welding time of 1.45 hr — the time needed to adjust the equipment for welding and to deposit the weld.

As shown in Fig. 13, joints were designed specifically to suit the penetration characteristics of the process used, with the root face of the joint for gas metal-arc welding being the deeper of the two. The greater depth was needed to prevent burn-through by the higher-amperage arc used for the single-pass weld.

An important feature of both welding processes was the use of low-carbon steel backing bars with a ceramic-coated groove against which the weld root surface was deposited to ensure full penetration. The ceramic coating, which prevented welding to the backing bar, covered the 0.060 to 0.065-in.-deep groove, as shown in Fig. 13, and the backing bar eliminated the need for a backing gas to shield the root surface.

Several ceramic materials for the backing bar were investigated, including aluminum oxide, magnesium zirconate, spinel, and zirconia. All but zirconia could be applied by flame spraying without excessive porosity. It was found that a coating thickness of 0.010 to 0.015 in. gave the required protection. The major difficulty was to obtain a uniformly dense coating that would resist burn-through and prevent welding to the backing bar. Because the ceramics were hygroscopic, the density of the coating was important. Moisture pickup by the more porous coatings caused porosity in the root-pass weld bead. Accordingly, the backing bars were heated to 250 F by built-in resistance heaters to dry the surface before welding and prevent moisture pickup. A coating of required density was obtained with plasma-arc-sprayed zirconia; two or more welds could be made before the backing bar had to be recoated.

Variables of the gas metal-arc process that were evaluated included diameter of the electrode wire, electrical requirements (current and voltage), travel speed, and distance from the contact tip to the work. Arc stability was maintained by holding the tip-to-work distance at 5/8 to 3/4 in. Since voltage was constant, arc length was automatically controlled. The arc condition, as well as the appearance of the weld puddle, provided a constant visual check of welding uniformity. Shielding-gas flow at the electrode holder was most efficient at a cup-to-work distance of 1/2 in.

Single-pass welds made with a 1/16-in.-diam electrode did not give complete penetration on the 3/8-in.-thick plate when used near maximum current density. When higher current was used, penetration was achieved, but it also resulted in erratic arc action and irregular weld shape. Satisfactory results were obtained by using 3/32-in.-diam electrodes. However, settings for current and travel speed had to be confined to a relatively narrow range for optimum weld crown height, penetration and shape.

As shown in Fig. 13, joint design for gas metal-arc welding was the same for the 3/8-in. and 7/16-in. thicknesses. Tests on single-pass welds in plates from 1/2 to 3/4 in. thick showed that the electrode could not fill the V and also give complete penetration. Thus, for the 9/16-in.-thick plate, the V was narrowed from 90° (45° bevel) to 76° (38° bevel), but the root-face width remained the same (45 to 50% of base-metal thickness).

Hardness readings taken across sections of the weld (after stress relieving but before tempering) indicated the following typical ranges: base metal, Rockwell C 5.5 to 13.5; heat-affected zone, Rockwell C 37 to 57.5; weld zone, Rockwell C 55 to 56. The difficulty of getting the vessel to the fixture for stress relief after welding without excessive cooling was eliminated by heating the backing bars to 650 F initially and reheating them by resistance whenever, during cooling, the temperature approached 300 F.

Temperature was controlled by thermocouples attached to the weldment in the area of the weld zone. Resistance heating elements were built into the fixturing of the shells and domes for preheating. Domes and shells were removed from the welding fixtures while at preheat temperatures and placed on stress-relieving fixtures, which were also heated by resistance.

Filler metals (electrodes) for welding heat-resisting alloy steels by the shielded metal-arc and gas metal-arc processes are presented in Table 27. Filler metals other than those shown have also produced satisfactory welds. The choice depends largely on specific joint requirements. The filler metals shown in the table will produce welds of 100% joint efficiency. Regardless of composition, all electrodes should be of the low-hydrogen type.

Although flux-cored arc welding is not used extensively for welding heat-resisting alloy steels, it is used at times (see Example 204 and Table 26).

Preheating. Preheating and interpass temperatures for heat-resisting alloy steels are determined by the composition and section thickness of the steel, as shown in Table 28. These temperatures are for average welding conditions, and are minimums. In general, maximum preheat and interpass temperatures should not exceed those listed in Table 28 by more than 150 F.

Preheating is generally preferred practice, and for compliance with specific codes it may be mandatory. Sometimes, however, as in Example 216, the steel can be welded without being preheated, because the welding conditions are more favorable than the average conditions on which the suggested temperatures in Table 28 are based. Conversely, when the conditions are less favorable than average, as with single-pass welds or welds made under severe restraint, preheating temperatures up to 150 F higher than those shown in Table 28 may be required.

Postweld Heat Treating. The need for postweld heat treating varies considerably for the steels listed in Table 25. The low-carbon steels (all grades of ASTM A335, and AISI 502) do not always require postweld heat treating. In most applications, these steels are postweld heat treated to develop specific properties (such as tensile and impact strength) without relation to the prior welding operation. After welding, the weldment should not be allowed to cool appreciably before being heated to the postweld heat treating temperature.

A 501 steel that contains more than 0.18% carbon should not be allowed to cool from the preheating and interpass temperature after welding until the weldment can be stress relieved at 1125 to 1250 F.

The high-temperature bolting steel (ASTM A193, grade B16) has high hardenability (almost as high as 4340) and is extremely susceptible to cracking. Weldments made from this steel should be kept at the preheat temperature during and after welding until they can be heated to the stress-relieving temperature of 1125 to 1250 F.

Among the steels listed in Table 25, H11 is the most susceptible to weld cracking. This steel is air-hardening and is almost certain to crack if allowed to cool in air directly from welding. Best practice for welding H11 is described in Example 205; the weldment is not permitted to cool before the final heat treatment — usually austenitizing, quenching and tempering.

Heat input and welding techniques discussed on page 213 in the section on High-Strength Alloy Steels Containing up to 0.25% Carbon (Quenched and Tempered) generally apply also for welding the heat-resisting alloy steels. It is especially important to use multiple passes and small stringer-type beads and if a weaving technique must be used, the width of weave should not exceed ⅜ in. or 2½ times the diameter of the electrode wire, whichever is less.

Tool Steels

The compositions of tool steels range from that of the plain low-carbon mold steel P1 to that of the high-alloy high speed steels, some of which have a total alloy content that exceeds 25%. It follows that their weldability also varies over a broad range.

Steels such as P1, like other plain low-carbon steels, can be welded without special procedures such as preheating and postheating. However, most tool steels have a high carbon content (some as high as 2.50%) and a relatively high content of alloying elements such as manganese, silicon, chromium, molybdenum, tungsten, vanadium and cobalt. Therefore, most tool steels require the use of carefully controlled preheating and postheating, and in most applications a considerable amount of welder skill is required.

Although tool steels, with a few exceptions such as the low-carbon mold steels, are relatively difficult to weld, many are arc welded for one of the following purposes:

1 Assembly of components into a tool
2 Fabrication of a composite tool by depositing an overlay of tool steel weld metal on specific areas of a carbon steel or a less highly alloyed steel (a shear blade, for example)
3 Rebuilding of worn surfaces and edges
4 Alteration of a tool or die to meet a change in design of the product being manufactured by use of the tool
5 Repair of cracked or otherwise damaged tools (see Examples 206 and 207).

For assembly of components (the first item above), the use of a low-cost steel as part of a tool assembly often permits the construction of tooling that is far more economical than if it were made entirely of tool steel. Moreover, this practice often permits use of a tougher steel to provide a backing for the tool steel portion. Purposes covered by items 2 and 3 in the above list represent most of the welding that is done on tool steels and constitute a special type of welding, described in the article on Hard Facing by Arc Welding, beginning on page 152 in this volume. The welding of tool steel described in the present article deals mainly with the repair of metalworking tools (item 5 in the preceding list).

Conditions for Welding. Tool steels (or tools) are preferably welded in the annealed condition, but often this is impractical as well as costly to the extent that any gain made possible by the use of weld repair would be nullified by the cost of annealing.

Tools and dies in the quenched and tempered condition can often be repaired by welding, but in such a case the preheating and postheating treatments for the base metal must not exceed the original tempering temperature. In some applications, therefore, the microstructure of the base metal, in addition to composition, influences the choice of filler metal.

General Guidelines. Most of the rules that apply to the welding of alloy steels apply also to the welding of tool steels, but as the alloy content or carbon content, or both, increase, the importance of adhering to these rules also increases. The following guidelines apply to the arc welding of all grades of tool steel.

1 Always use the smallest-diameter electrode that will do the job.
2 Prepare the surface by machining or grinding. A crack should be gouged out to a U-shape, never to a V-shape, because sharp angles will promote cracking.
3 Grind or machine away all of the existing cracks, and provide at least 1⁄16 in. of excess weld metal for finish grinding.
4 Make sure that all electrodes and base-metal surfaces are clean and dry before welding. Absolute freedom from oil and grease is essential.
5 Insofar as possible, position the work so that weld beads are laid slightly uphill. This aids joint penetration.
6 Never weld any tool steel that is at room temperature; the recommended preheating temperature must be adhered to.
7 Keep heat input to the minimum; use minimum arc voltage and amperage, and reduce amperage for secondary and finishing passes.

Table 27. Suggested Electrodes for Shielded Metal-Arc and Gas Metal-Arc Welding of Heat-Resisting Alloy Steels

Steel	Shielded metal-arc	Gas metal-arc
ASTM A335, grade P1	E7018-A1	E70S-6
grade P12	E8016-B2	E70S-1B
grade P11	E8016-B2	E70S-1B
grade P22	E9015-B3	2.25% Cr wire
grade P7	E505 or E309	ER502 or ER309
grade P9	E505 or E309	ER502 or ER309
ASTM A193, grade B16	E11018-M	E70S-1B
AISI 501	E502	ER502
AISI 502	E502	ER502
H11 tool steel	....	H11 wire(a)

(a) Carbon content should be no higher than that of the base metal and preferably lower; ER502 electrode wire has been successfully used.

Table 28. Preheat and Interpass Temperatures for Wrought Heat-Resisting Alloy Steels

Steel	Preheat and interpass temperature, F, for section thicknesses, in., of: Up to ⅜	⅜ to ¾	¾ to 1½
ASTM A335, grade P1	None(a)	200	200
grade P12	None(a)	200	250
grade P11	None(a)	200	250
grade P22	200	250	300
grade P7	400	500	550
grade P9	500	600	650
ASTM A193, grade B16	400	500	600
AISI 501	350	450	550
AISI 502	None(a)	300	400
H11 tool steel	350(b)	500(b)	600(b)

(a) Assuming that the base metal is near room temperature. If base metal is colder than 50 F, it should be preheated to at least 70 to 100 F. (b) After welding is completed, the weldment should be held at the interpass temperature until reheating for austenitizing begins.

8 Travel slowly and straight, using narrow stringer beads rather than heavy deposits; avoid weaving.
9 Deslag and wire brush thoroughly between passes.
10 Peen lightly immediately after each bead has been deposited. The weld metal must be peened while it is at 700 F or higher; never peen when the weld metal is cold. Peening helps to relieve shrinkage stresses, minimizes distortion, and improves the mechanical properties of the weld.

Welding Processes. Repair of tools by welding is most often done by shielded metal-arc welding. The principal reasons for the use of this process are flexibility in welding position and location, simple equipment that can be quickly moved about, and the wide variety of filler-metal compositions available as covered electrodes.

The other arc welding processes, though, are not precluded. All of them have been used under certain conditions for the welding of tool steels. For instance, submerged-arc welding is often used for repair welding of large tools such as rolls.

The two examples that follow describe techniques for repair welding. The first example deals with repairing of a cracked die by shielded metal-arc welding, and the second describes how defects in a large roll casting were repaired by submerged-arc welding.

Example 206. Repair Welding of a D2 Tool Steel Die (Fig. 14)

The punch-and-draw die shown in Fig. 14 was made from D2 tool steel and was used for blanking and drawing steel shells from low-carbon steel sheet 0.075 in. thick. Improper operating conditions caused the crack, which propagated completely through the sidewall of the die, as shown in Fig. 14. The cracked sidewall was successfully repaired by shielded metal-arc welding, in spite of the difficulty generally encountered in obtaining sound welds in D2 tool steel. [Because of its composition (1.5% C, 12% Cr, 1% Mo), D2 tool steel is air-hardening. In addition to its extremely high hardenability, the microstructure of the steel is characterized by massive alloy carbides. Both of these conditions contribute to its high susceptibility to weld cracking.]

As shown in Fig. 14, the crack was repaired by a partial-penetration weld, rather than by welding the entire crack. The groove for the weld was cut, by grinding, to less than the full depth and length of the crack. During preheating to 800 ± 100 F, a slight excess of heat was applied to the cracked side with an oxyacetylene torch to open the crack so that any particles lodged in the crack could be removed with a piece of music wire. A temperature-indicating crayon for 800 F was used to check preheat temperature, which was maintained during welding.

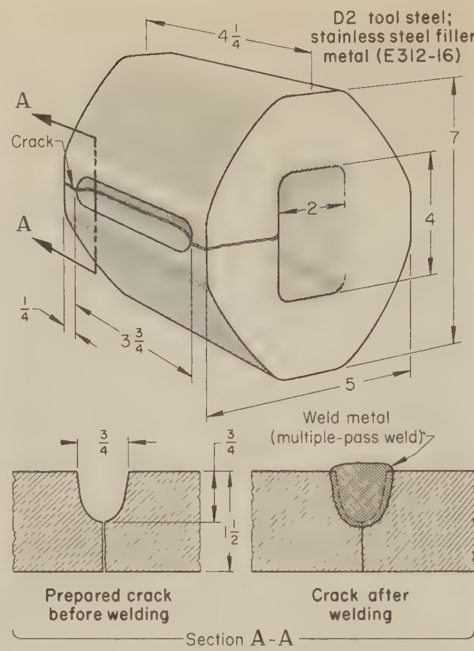
The weld was made with E312-16 stainless steel electrodes. Welding current was kept as low as possible. Short stringer beads, approximately 1 in. long, were deposited with minimum penetration; weaving was carefully avoided. Welding details are given in the table with Fig. 14.

Success of the operation depended greatly on the effective use of peening. Immediately after it was deposited, each weld bead was vigorously peened while it was still hot, using an air-operated or electrically operated gun, with a rounded thin-edge tool equivalent to a dull chisel. Peening the hot weld metal not only helped to produce a more favorable stress pattern (the most common reason for peening a weld), but in this application also helped to prevent a continuous formation of alloy carbides at the grain boundaries.

The crack closed after deposition of each of the first few beads, but reopened after each of the first few peening operations. Peening did not appear to open the crack when the groove was about one-fourth filled, but peening was just as essential from this point on and was done with equal thoroughness for the remaining beads. After welding, the die was allowed to cool slowly to room temperature out of drafts. The die was postheated in a furnace at 800 F and air cooled.

As an alternative, an oxyacetylene torch could be used for both preheating and postheating. When a torch is used, it is important to have a neutral flame with a large tip, and to heat the die slowly and uniformly over the entire surface. When a torch is used for postheating, the die should be buried in lime immediately after welding and postheating, and held there for 12 hr.

Cost savings realized with this repair welding operation were significant. The welding required approximately 8 man-hr and $5 for material, compared with 50 man-hr and $50 for material for a new die. Die repairs by welding in one shop that used techniques similar to those described above were 98% successful.



Conditions for Shielded Metal-Arc Welding

Joint type	Butt
Weld type	Partial-penetration U groove
Welding position	Flat
Preheat	800 ± 100 F
Postheat	800 F(a)
Electrode wire	⅛-in.-diam E312-16
Power supply	300-amp rectifier
Current	150 to 200 amp, dcrp
Hot peening	Required; applied to each bead

(a) For furnace heating, 800 F for 2 hr. For torch heating, after heating to 800 F, bury in lime for 12 hr.

Fig. 14. Punch-and-draw die that cracked in service and was repaired by shielded metal-arc welding (Example 206)

Example 207. Weld Repair of Casting Tears in a High-Carbon Alloy Steel Roll (Fig. 15)

The large cast alloy steel mill roll illustrated in Fig. 15 was produced to the following composition: 1.0 C, 0.9 Mn, 0.5 Si, 0.038 S, 0.038 P, 1.0 Cr, 0.5 Ni and 0.5 Mo. During rough machining of the roll neck to within ⅛ in. of finished size, a number of short discontinuous casting tears or cracks appeared. The cracks were completely removed by cutting a circumferential groove of the size shown in section A-A in Fig. 15; absence of the defects was confirmed by dye-penetrant inspection. The defective area was then repaired by automatic submerged-arc welding.

Previous repair welding experience had shown that local preheating was ineffective because of the heat sink effect of the large mass. Therefore, after machining and degreasing of the groove, the roll casting was heated slowly to 750 F in a furnace over a period of 27 hr (1 hr per inch of body radius). When the casting was removed from the furnace it was completely covered with asbestos cloth, except for the area to be welded, and was positioned in a lathe for rotation in the horizontal position. The lathe was equipped with an automatic stepping carriage on which the submerged-arc welding head was mounted. A gas burner was placed under the roll for use if the interpass temperature dropped below 700 F, but this did not occur and welding was completed without the need for additional heat.

The electrode was selected for good color match and toughness, and to provide a deposit that would be equal in hardness to that of the base metal. A tubular electrode was used, consisting of a low-carbon steel sheath and a core of neutral flux and alloying elements. Typical composition of as-deposited weld metal was 0.10 C, 1.35 Mn, 0.75 Si, 2.0 Cr and 1.0 Mo.

The roll was submerged-arc welded under the conditions tabulated with Fig. 15. These conditions had been shown by earlier tests to provide the most desirable bead shape with maximum deposit thickness and minimum deposit dilution. There was some carbon pickup that caused increased hardness at the bond line, but the condition was acceptable. The weld metal was built up to approximately ¼ in. above the surface of the roll neck (see section A-A in Fig. 15) by stringer beads deposited about ½ in. wide with a buildup of about 3/16 in. A bead overlap of about 40% was obtained by setting the stepping carriage for a 5/16-in. advance after each pass.

After being welded, the roll was placed in a furnace and cooled slowly to 600 F, at which temperature the metal in the weld zone that had been above the austenitizing temperature was transformed to bainite. The roll was then heated to 750 F (the specified tempering temperature) at 15 F per hour and cooled to room temperature in 50 hr.

After heat treatment, the weld buildup was machined flush with the roll-neck surface and dye-penetrant inspected. The deposit was found to be free from cracks and porosity and was therefore checked for hardness, ground to finish dimensions, and polished in a roll grinder.

Selection of Filler Metal (Electrodes). The factors that must be considered in the selection of an electrode for arc welding of tool steel are: (*a*) composition of the base metal, (*b*) heat treated condition of the base metal (annealed or hardened), and (*c*) service requirements of the welded area — that is, whether the weld is located at a critical working surface such as a cutting edge or in an area of high wear. Typical electrode compositions (deposit analyses) are presented in Table 29. The selections listed in this table are based on the assumption that the welded area is a working surface of the tool and, therefore, must have approximately the same hardness, or be capable of achieving the same hardness, as the base metal. Selection of an electrode is often simplified when this requirement does not have to be met.

When welding annealed tools, the composition of the deposited weld metal should approximate that of the base metal, so that the weld and base metal will respond similarly to heat treatment and will develop the same hardness after heat treatment.

Selection of electrodes for welding hardened tools requires more consider-

ation than for welding annealed tools. If the weld metal is to be deposited at a functional area of the tool (such as a cutting edge), it is necessary to select a filler metal that will harden as it cools. Under these conditions, the composition of the deposited weld metal may be entirely different from that of the base metal.

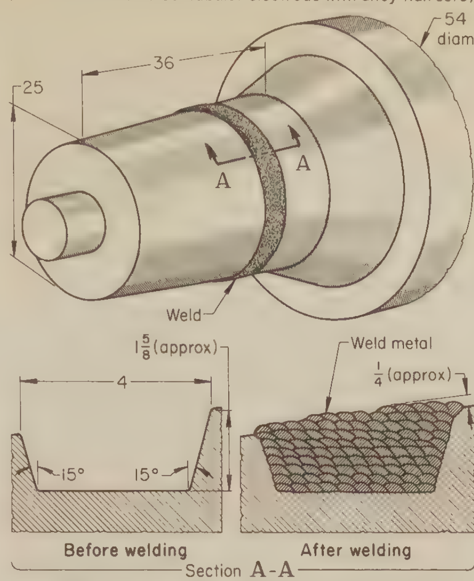
Another technique that is often used in repair welding of hardened tools when the weld will be in a working area is to begin the weld with an electrode that deposits weld metal that hardens only slightly or not at all on cooling — for example, a stainless steel or a low-hydrogen low-alloy steel electrode. A major portion of the weld is made with one of these electrodes, but approximately 3/16 in. of the weld depth is left for completing the weld with an electrode that deposits approximately the same composition as the base metal. This final layer may need to be thicker than 3/16 in., depending on the stresses to which it will be subjected. However, this procedure should not be used if the welded tool will be quenched and tempered, because it will be likely to crack.

When high hardness is not required in the welded area, the most common practice is to make the entire weld with a low-alloy, stainless steel, or nickel-base alloy electrode.

Preheat and Interpass Temperature. Regardless of composition or condition (annealed or hardened), tools should never be welded without preheating. Preheating temperature varies with tool steel composition. Sometimes, a steel of a given composition is preheated at different temperatures depending on whether it is in the annealed or the hardened condition. Preheating temperatures commonly used for various grades of tool steel in both annealed and hardened conditions are given in Table 29; as will be seen from the table, preheating temperatures range from 250 F for the water-hardening tool steels (W grades) to 1200 F for annealed hot work steels (H grades). When a temperature range, as opposed to a specific temperature, is shown (for instance, 250 to 450 F for W1 and W2), the lower temperature of the range is used for thin sections and the higher temperature for thick sections and massive tools. The minimum preheating temperature should always be maintained as the interpass temperature during welding.

Postweld Heat Treating. When welding annealed material, best practice

1% carbon alloy steel; Cr-Mo steel filler metal (from low-carbon steel tubular electrode with alloy-flux core)



Conditions for Submerged-Arc Welding

Weld type	Circumferential single-V groove
Preparation	Machined to remove cracks
Welding position	Flat(a)
Number of passes	About 102 (10 layers)
Preheat	750 F, in a furnace
Postheat	See text
Electrode wire	5/32-in.-diam low-carbon steel(b)
Flux	Neutral, with alloy content
Flux consumption	15 lb per hour
Bead width	½ in., 40% stepover
Power supply	Constant-voltage motor-generator
Current	500 to 550 amp, dcrp
Voltage	25 to 27 v
Electrode stickout	1½ in.
Travel speed	20 in. per minute
Deposition rate	10 lb per hour
Finishing	Machined and ground
Auxiliary equipment	Roll lathe, flux-recirculating system, automatic stepping carriage

(a) Horizontal rolled pipe position. (b) An unclassified low-carbon steel tubular electrode with a core containing flux and alloying elements. Typical weld deposit was 0.10 C, 1.35 Mn, 0.75 Si, 2.0 Cr, 1.0 Mo.

Fig. 15. Large cast alloy steel mill roll that was salvaged by automatic submerged-arc welding (Example 207)

is to allow the weldment to cool to about 150 F, and then to heat it within the appropriate temperature range (see Table 29). When dealing with hardened base metal, the postheating temperature must not exceed the original tempering temperature if the hardness of the tool is to be retained. Common practice is to heat at 25 to 50 F below the original tempering temperature.

Shielded Metal-Arc Welding

Most alloy steels discussed in this article can be successfully joined by shielded metal-arc welding. This process offers the same advantages for welding alloy steels as it does for plain low-carbon steels (see the article on Shielded Metal-Arc Welding, which begins on page 1 in this volume).

Shielded metal-arc welding is more versatile than the other arc welding processes for work to be done in the field or in drafty areas, because less equipment is required and because under adverse conditions the shielding obtained from decomposition of the electrode covering during welding is more dependable than gas shielding.

An important advantage of the shielded metal-arc process for welding alloy steel is that flux-covered electrodes (filler metals) are available in a wide range of standardized compositions (see Tables 5, 19 and 27). Because the slag covering the weld metal retards cooling, it is sometimes an advantage in welding alloy steel.

The major disadvantages of the shielded metal-arc process for welding alloy steels are those encountered in the welding of other metals — namely, the variation in weld quality, and the loss of time that results from frequent interruptions to replace spent electrodes. This loss of time can be greater for alloy steels than for mild steels because alloy steels generally are welded with smaller-diameter electrodes, and thus electrodes have to be replaced more often. Also, the frequent stops make it more difficult to control interpass temperature — a critical factor in some alloy steel applications.

As with all metal-arc welding processes, composition of the weld deposit is more difficult to control than when the deposit has been produced by a process such as gas tungsten-arc welding in which the filler metal is fed directly into the weld puddle without passing through the arc.

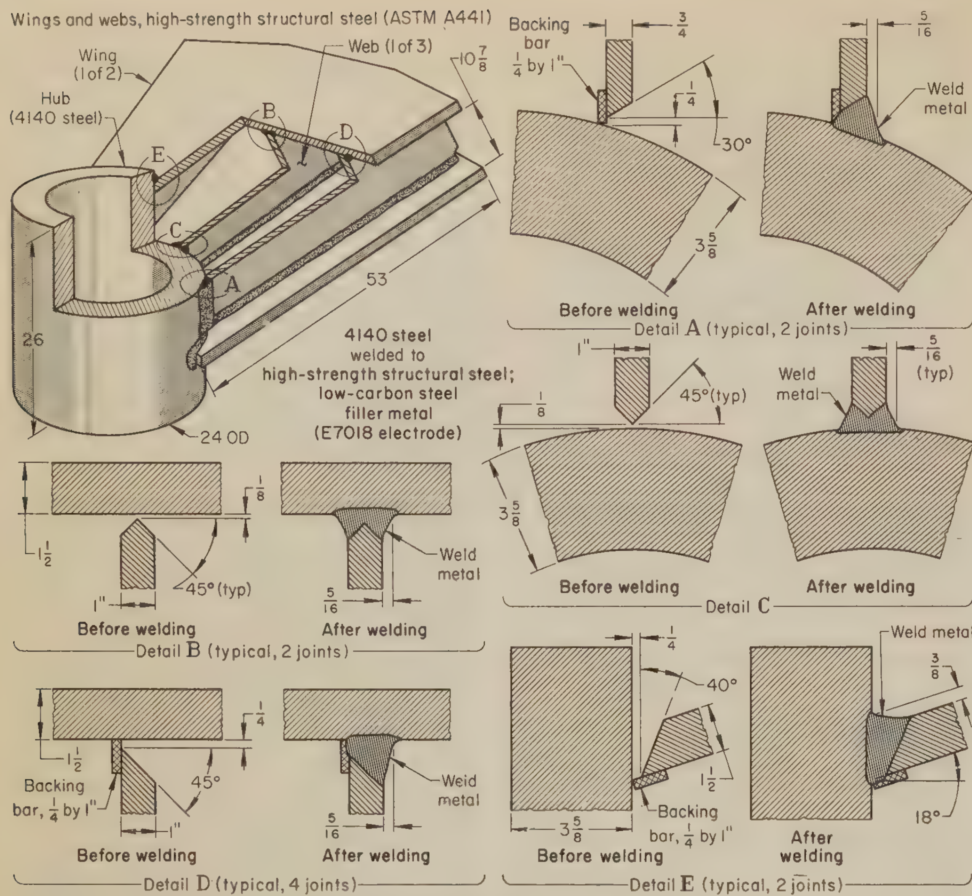
The use of low-hydrogen electrodes and close control of moisture content in the electrode covering are essential if the danger of underbead and toe cracking is to be minimized (see preceding sections of this article, especially pages 205 to 207).

Production Examples. Detailed descriptions of practice used in shielded metal-arc welding of several different types of alloy steel are presented in the four examples that follow (see also Examples 196, 198 and 206).

Table 29. Conditions for Arc Welding of Tool Steels

		Annealed base metal						Hardened base metal	
Steel (AISI type)	Type of tool steel electrode(a)	Annealing temperature, F	Preheat and postheat temperature, F	Hardening temperature, F	Quenching medium	Tempering temperature, F	Resulting hardness, Rockwell C	Preheat and postheat temperature, F	Rockwell C hardness(b)
W1, W2	Water hardening(c)	1375 to 1425	250 to 450	1375 to 1475	Water	300 to 650	54 to 65	250 to 450	56 to 62
S1	Hot work(d)	1475	300 to 500	1750	Oil	300 to 500	54 to 57	300 to 500	52 to 56
S5	Hot work(d)	1450	300 to 500	1625	Oil	500 min	55 to 59	300 to 500	52 to 56
S7	Hot work(d)	1500 to 1550	300 to 500	1725	Air(e)	400 to 425(f)	56 to 58	300 to 500	52 to 56
O1	Oil hardening(g)	1450	300 to 400	1475	Oil	300 to 450	61 to 63	300 to 400	56 to 62
O6	Oil hardening(g)	1425 to 1450	300 to 400	1450 to 1500	Oil	300 to 450	61 to 63	300 to 400	56 to 62
A2	Air hardening(h)	1650	300 to 500	1775	Air	350 to 400(f)	60 to 61	300 to 400	56 to 58
A4	Air hardening(h)	1425	300 to 500	1550	Air	350 to 400(f)	60 to 61	300 to 400	60 to 62
D2	Air hardening(h)	1650	700 to 900	1850	Air	900 to 925(f)	58 to 60	700 to 900	58 to 60
H11, H12, H13	Hot work(d)	1600(j)	900 to 1200	1850	Air	1000 to 1150(f)	40 to 50	700 to 1000	46 to 54
M1, M2, M10	High speed(k)	1550(j)	950 to 1100	(m)	Salt(e)	1000 to 1050(f)	65 to 66	950 to 1050	60 to 63

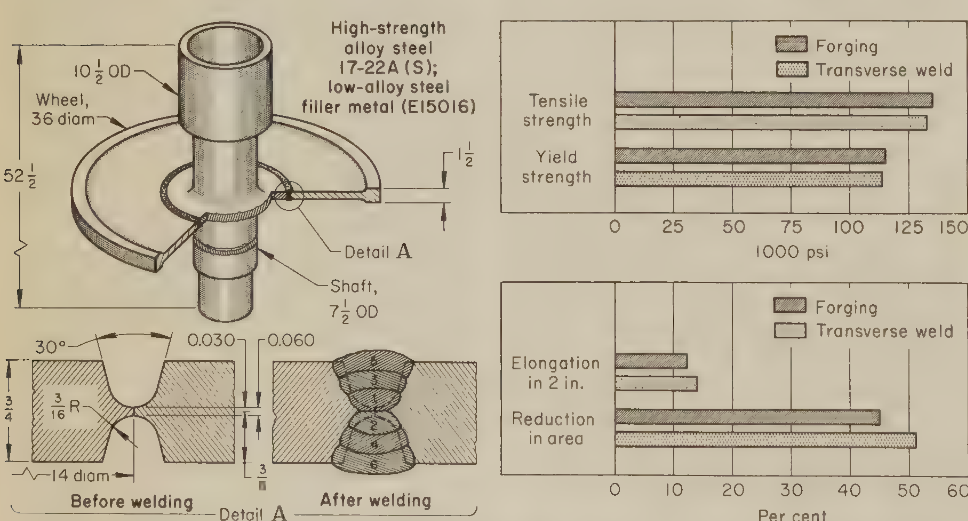
(a) Nominal compositions of weld deposits are footnoted by type. The compositions of proprietary electrodes vary. (b) As-deposited after postheat. (c) Deposit: 0.95 C, 0.20 Si, 0.30 Mn, 0.20 V. (d) Deposit: 0.33 C, 1.00 Si, 0.40 Mn, 5.00 Cr, 1.35 Mo, 1.25 W. (e) Oil may also be used. (f) Double temper recommended. (g) Deposit: 0.92 C, 0.30 Si, 1.28 Mn, 0.50 Cr, 0.50 W. (h) Deposit: 0.95 C, 0.30 Si, 0.40 Mn, 5.25 Cr, 1.10 Mo, 0.25 V. (j) For H12 and M2 steels, anneal at 1625 F. (k) Proprietary compositions. (m) 2240 F for M1, 2260 F for M2, 2215 F for M10.



Conditions for Shielded Metal-Arc Welding

Joint type	T
Weld type	Single-bevel and double-bevel groove
Welding positions	All
Preheat	400 F
Interpass temperature	200 F min
Postheat	Cooled slowly in special furnace
Electrode	3/16-in.-diam E7018
Power supply	400-amp motor-generator
Current	250 amp, dcrp
Voltage	25 v
Welding time per assembly	24 hr

Fig. 16. Floodgate-trunnion hub assembly that was welded in a preheat furnace on which the sides and top opened for welder access (Example 208)



Conditions for Shielded Metal-Arc Welding

Joint type	Circumferential butt
Weld type	Double-U groove
Welding position	Flat
Number of passes	Six
Power supply	Constant-current motor-generator
Preheat	600 F(a)
Interpass temperature	500 to 700 F
Postheat (stress relief)	1065 F, 2 hr; air cool
Electrode wire	5/32-in. diam, low hydrogen(b)
Current:	
Passes 1 and 2	120 to 130 amp, dcrp
Passes 3 to 6	170 to 180 amp, dcrp
Voltage	23 to 26 v

(a) See text for details. (b) Tensile strength, 150,000 psi; formerly designated E15016.

Fig. 17. Gas-turbine compressor wheel that was welded by the shielded metal-arc process because of the adaptability of the process to small quantities (Example 209)

Example 208. Use of a Preheating Furnace Designed To Give Welder Access to Assembly (Fig. 16)

The floodgate-trunnion hub assembly shown in Fig. 16 required preheating and the maintenance of interpass temperatures to produce sound welds. The hub portion was made from an alloy steel forging of 4140 composition meeting the requirements of ASTM A237. The two wings and three webs were made of high-strength structural steel plates conforming to ASTM A441 specification (0.26 C max, 1.30 Mn max, 0.05 P max, 0.063 S max, 0.01 V min, and 0.18 Cu min; 67,000 psi tensile, 46,000 psi yield, and 18% elongation in 8 in.).

Shielded metal-arc welding was selected because it was the most practical process for this assembly, which involved all welding positions and five different joint designs. The joint designs, before and after welding, are shown in Fig. 16. The assembly required a preheat of 400 F and a minimum interpass temperature of 200 F.

The preheat was supplied by a specially constructed furnace that consisted of an insulated box, which measured 7 ft long by 7 ft wide by 3 ft deep, and, under the box, a burner made of 1¼-in. standard pipe drilled to provide ⅛-in.-diam holes for gas ports. The top of the box was removable and two sides could be swung back, to allow the welder access to the joints. Temperature of the assembly was maintained at 200 to 300 F during welding. Welding was discontinued when the temperature dropped to 200 F, at which point the boxlike furnace was closed and the temperature was allowed to recover to 300 F before the box was opened and welding was resumed. The welding sequence was:

1. Tack weld, then weld, the two wings to the center web (detail B in Fig. 16)
2. Weld the wings and center web to the hub (details C and E in Fig. 16)
3. Tack and then weld the two outside webs to the wings (detail D in Fig. 16) and to the hub (detail A).

After being welded, the assembly was allowed to cool slowly in the furnace with the burners shut off. Additional welding details are given in the table that accompanies Fig. 16.

Example 209. Turbine Wheels of High-Strength Alloy Steel Welded by the Shielded Metal-Arc Process (Fig. 17)

Because only six of the assemblies were needed, and because of the simplicity of developing procedures for the process, shielded metal-arc welding was selected for joining a shaft to a compressor wheel for a gas-turbine engine (see Fig. 17).

The wheel and shaft were of 17-22A(S) steel (see Table 21 for composition) in the annealed condition at a maximum hardness of 179 Bhn. The weld groove shown in detail A in Fig. 17 was machined in the wheel and shaft, and the parts were degreased and wiped with acetone before being preheated in a furnace. Initially, the shaft was preheated to 600 F and, because the shaft hole in the wheel was 0.002 in. undersize to give a press fit, the wheel was preheated to 800 F, to produce the additional expansion needed for clearance. The temperature of the assembly was equalized at 600 F after the assembly was placed in a welding positioner. The preheat temperature of 600 F reduced the cooling rate and was close enough to the M_s temperature (630 F) of the steel to prevent the formation of martensite in austenitized areas.

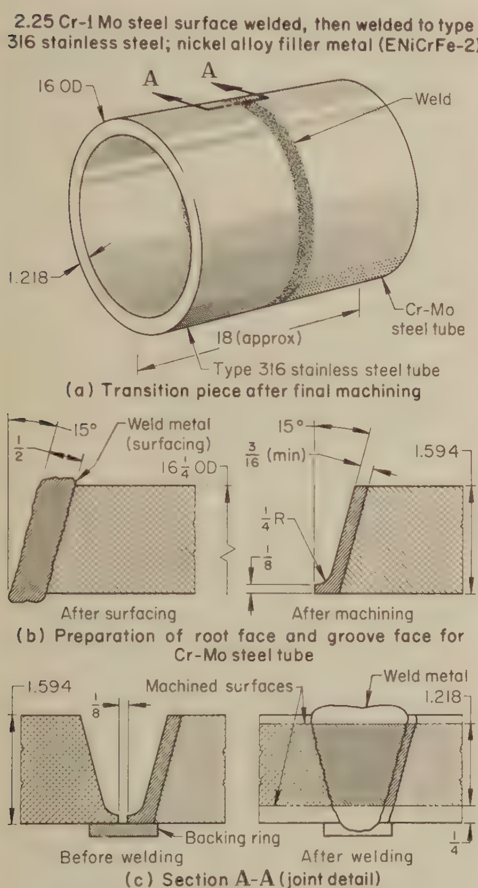
The preheat temperature, which was maintained throughout the welding operation by means of a circular gas burner located beneath the joint, was held in the range of 500 to 700 F, as measured by a surface pyrometer.

The welding sequence, shown in Fig. 17, consisted of six passes — the first two at a current of 120 to 130 amp to deposit stringer beads, and the remaining passes at 170 to 180 amp to fill the joint. Slag was removed after the first pass, and the bead was wire brushed, before the assembly was turned

over in the fixture for the second pass. The current range selected for the first two passes gave 100% penetration of the 0.060-in. root face. The remaining four passes were made at the higher current and with a weave technique to obtain the deposition needed to fill the joint. Immediately after being welded, the assemblies were stress relieved at 1065 F for 2 hr, followed by air cooling, and the welds were then machined flush and inspected by radiographic and magnetic-particle techniques.

Final treatment consisted of normalizing for 1 hr at 1750 F, air cooling, tempering for 6 hr at 1200 F, and air cooling.

The weld metal had the following composition: 0.11 C, 0.36 Mn, 0.62 Si, 0.45 Cr, 0.14 V, 0.64 Mo, 1.68 Ni, 0.007 P and 0.015 S. The weld metal responded favorably to heat treatment, resulting in a hardness of Rockwell C 23 to 26, compared with Rockwell C 27 to 35 for the base metal. Mechanical properties of the weld in the transverse direction (Fig. 17) were comparable to those of the base metal and within specified requirements. Additional welding details are given with Fig. 17.



Conditions for Shielded Metal-Arc Welding

Joint type	Butt
Weld type	Surfacing; single-U groove
Welding position:	
Surfacing	Flat
U-groove weld	Horizontal rolled
Number of passes	Variable(a)
Preheat (for surfacing only)	300 F
Postheat (stress relief)	1275 F for 8 hr(b)
Electrode wire:	
Surfacing	ENiCrFe-2
U-groove welding	3/32, 1/8 and 5/32-in.-diam ENiCrFe-2
Power supply	300-amp rectifier
Current (dcrp) and voltage, U-groove welding:	
3/32-in. wire	50-70 amp, 18-22 v
1/8-in. wire	80-100 amp, 20-25 v
5/32-in. wire	120-140 amp, 20-26 v

(a) As required for filling to dimensions. (b) In furnace with sulfur-free atmosphere.

Fig. 18. Machined shielded metal-arc welded transition piece consisting of a stainless steel tube and an alloy steel tube that was surface welded and machined before being joined to the stainless tube (Example 210)

Example 210. Welding Alloy Steel to Stainless Steel To Produce a Transition Piece (Fig. 18)

The transition piece shown in Fig. 18(a), consisting of thick-wall tubes of type 316 stainless steel and 2¼Cr-1Mo (ASTM A335, grade P22) alloy steel — the same dissimilar metals as were to be welded in a field installation — was shielded metal-arc welded under favorable shop conditions to ensure a sound weld and to prevent carbide precipitation in the stainless steel. The transition piece could then be welded into place in the field, using conventional procedures.

A 15° bevel was machined on one end of the 2¼Cr-1Mo tube, the tube was preheated to 300 F, and the joint surface was "buttered" with a ½-in. thickness of nickel alloy (ENiCrFe-2) filler metal, deposited in successive layers (see "After surfacing" view in Fig. 18b). Each weld layer was carefully cleaned of slag, and liquid-penetrant inspected for defects.

After being built up to full thickness, the surface weld deposit was machined to the shape and dimensions shown in the "After machining" view in Fig. 18(b). The stainless steel tube was machined to the same configuration, and the two tubes were assembled, with a low-carbon steel backing ring as shown in Fig. 18(c), for welding in the horizontal rolled position. The resulting joint was welded without preheat, using the same filler metal (ENiCrFe-2), cleaning method and inspection procedure as were used for surfacing. Additional welding conditions are given in the table that accompanies Fig. 18.

After welding, the assembly received a postweld heat treatment at 1275 F for 8 hr to temper and stress relieve the heat-affected zone of the 2¼Cr-1Mo tube without causing excessive carbon migration. A sulfur-free furnace atmosphere was employed, in order to prevent sulfur embrittlement of the ENiCrFe-2 weld deposit.

The transition piece was machined to size, internally and externally. As shown in Fig. 18(c), the weld metal was removed completely at the root of the joint, where dilution had resulted from the use of a low-carbon steel backing ring. This machining operation also removed any root defects. The final surfaces, which were free of any weld reinforcement, received liquid-penetrant and radiographic inspection.

Transition pieces of this type were used on other dissimilar-metal joints. For joining piping systems of 347 stainless steel to 2¼Cr-1Mo alloy steel, the same procedure, in general, was followed, but in this application the 347 tube was also surface welded, using a 16Cr-8Ni-2Mo filler metal, before the final groove weld was deposited with ENiCrFe-2 filler metal.

Example 211. Welding Alloy Steel Bucket Teeth to an Austenitic Manganese Steel Lip Section (Fig. 19)

As shown in Fig. 19, a casting of austenitic 12% manganese steel constituted the lip section of a bucket used in stacking coal, coke and cinders. The bucket lips were cast with six rectangular platforms, to each of which an alloy steel tooth was to be welded. The low-carbon low-alloy high-strength steel from which the teeth were cast was in the quenched and tempered condition. Welding these dissimilar alloys presented the problem of keeping the austenitic manganese steel relatively cool, to avoid embrittlement, while the base of the alloy steel tooth was preheated, to avoid underbead cracking.

Satisfactory joints were produced by two welding procedures, both employing the shielded metal-arc process and the joint design shown in Fig. 19. A stainless steel filler metal that was capable of absorbing shrinkage stresses without cracking was used in both procedures.

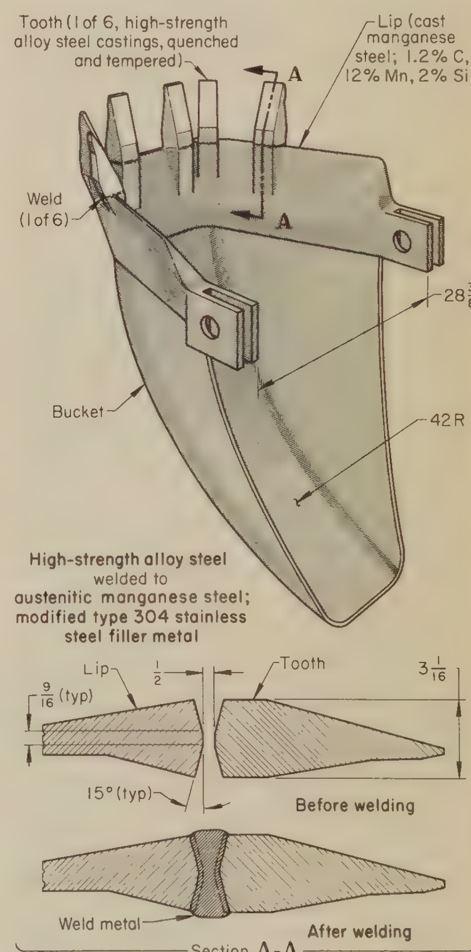
One procedure consisted of separately preheating the teeth to 400 F, applying a surfacing pass, tack welding the teeth in position, and welding without further preheating.

In the other procedure, the teeth were tack welded to the lip and the weld was made with a 400 F preheat that was applied only to the base of the teeth. The preheating was done with a torch.

The composition of the stainless steel covered electrode was: 0.14% max C, 4.0 to 4.5% Mn, 19% min Cr, and 9% min Ni. Mechanical properties of undiluted weld metal from this electrode were: tensile strength, 90,000 psi; yield strength, 67,000 psi; and elongation in 2 in., 44%. Attempts to weld the joints using E309 and E310 electrodes resulted in cracking in the heat-affected zones of the teeth, even though both of these electrodes normally provided a weld deposit as tough and ductile as the electrode used for the successful welds.

Flux-Cored Arc Welding

Flux-cored arc welding can be used to join most of the alloy steels dealt with in this article. This automatic or semiautomatic process is considerably



Conditions for Shielded Metal-Arc Welding

Joint type	Butt
Weld type	Double-V groove
Preheat	400 F (tooth base only)
Postheat	None
Filler metal	Proprietary stainless steel(a)

(a) Electrode composition was: 0.14% max C, 4.0 to 4.5% Mn, 19% min Cr, 9% min Ni.

Fig. 19. Bucket with a lip cast from 12% Mn steel to which six teeth cast from a high-strength alloy steel were joined by shielded metal-arc welding (Example 211)

faster than shielded metal-arc welding, because it utilizes a continuously fed electrode wire (see the article on Flux-Cored Arc Welding, which begins on page 24 in this volume). It is particularly suitable for production applications where high deposition rates are desirable. Because the flux-cored arc process enables welding to proceed with fewer interruptions, control of interpass temperature, which is an important factor in welding alloy steels, is better than when shielded metal-arc welding is used.

Flux-cored arc welding has essentially the same limitations for welding alloy steels as for welding plain low-carbon steels. When an auxiliary gas shield is used, flux-cored arc welding is less satisfactory than shielded metal-arc welding for use in drafty locations. The equipment for both the auxiliary gas-shielded and the self-shielding methods of flux-cored arc welding is more elaborate and less portable (especially for the auxiliary gas-shielded method) than the equipment needed for shielded metal-arc welding.

Electrodes. A major advantage of the flux-cored arc process in the welding of alloy steels is that the cores of tubular electrode wires can be formulated in almost any required composition to suit specific applications (see Example 200). The flux-cored wire consists of the sheath portion, which is always low-carbon steel, and the core, which contains alloying elements and flux, both in powder form. Thus, it is practical to produce small quantities of electrode wire of virtually any special composition that may be needed. Alloy-containing flux-cored electrode wires that meet standard specifications are not available to the same extent as flux-covered electrodes for shielded metal-arc welding. Most of the flux-cored electrode wires for welding alloy steel are marketed as proprietary compositions.

Table 21 on page 42 in the article on Flux-Cored Arc Welding gives compositions and mechanical properties of weld metal from an alloyed basic flux-cored electrode.

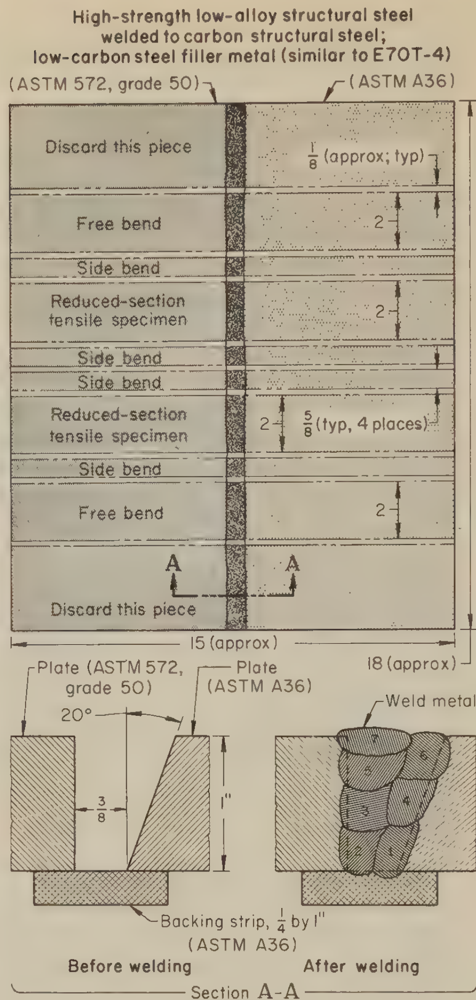
Shielding Gas. Carbon dioxide is used almost exclusively as shielding gas for auxiliary gas-shielded flux-cored arc welding. For alloy steels, the carbon dioxide must be of welding grade (dew point, −40 F or lower). Although welding-grade carbon dioxide is also recommended for welding plain low-carbon steels, the low dew point is of greater importance in welding alloy steels.

Shielding gases composed of 75% argon and 25% carbon dioxide, and of 98% argon and 2% oxygen, have also been successfully used for welding alloy steels, but these gas mixtures cost more than carbon dioxide and, since they usually do not provide any improvement in results, their use is seldom justified.

Self-shielding flux-cored arc welding can be used outdoors or in drafty locations indoors. Whether or not the self-shielding method is acceptable for welding alloy steels depends on weld-quality requirements.

Production Examples. Details of practice that have proved successful for welding of several alloy steels by flux-cored arc welding are presented in Examples 199, 200 and 204, and in the two examples that follow.

Before a flux-cored arc welding procedure is used in production welding, it should be qualified using the same materials as those to be welded in production practice. The first of the two examples that follow gives details of a qualification test for self-shielding flux-cored arc welding. The second of these examples describes a production application of flux-cored arc welding with auxiliary gas shielding.



Conditions for Flux-Cored Arc Welding

Joint type	Butt
Weld type	Single-bevel groove
Welding method	Semiautomatic, self-shielding
Electrode holder	Hand held, air cooled
Electrode wire	0.120-in.-diam(a)
Welding position	Flat
Wire-feed speed	125 in. per minute
Preheat	70 F
Postheat	None
Current	400 to 425 amp, dcrp
Voltage	27 to 28 v
Welding speed:	
Root passes 1 and 2	9 to 10 in. per minute
Subsequent passes	17 to 19 in. per minute

Results of Procedure-Qualification Tests

Tension tests(b):
1 83,000-psi tensile strength, break in base metal
2 80,600-psi tensile strength, break in base metal

Side-bend tests:
1 Defect under ⅛ in. — passed
2 Defect under ⅛ in. — passed
3 Defect under ⅛ in. — passed
4 No defect — passed

Free-bend tests(c):
1 41.8% elongation
2 43.5% elongation

(a) Similar to E70T-4; see text. (b) Reduced-section tensile specimens, 0.958 in. thick by 1.503 to 1.502 in. wide. (c) Not mandatory for qualification.

Fig. 20. Test plate used to qualify a procedure for self-shielding flux-cored arc welding. Table gives principal welding conditions and results of the qualification tests. (Example 212)

Example 212. Qualifying a Procedure for Self-Shielding Flux-Cored Arc Welding of High-Strength Low-Alloy Structural Steel to Carbon Structural Steel (Fig. 20)

To obtain procedure qualification for self-shielding flux-cored arc welding, a fabricator and erector of structural steel followed the rules given in the AWS Code for Welding in Building Construction (D1.0). This fabricator sought a qualified status for code conformance for flux-cored arc welding procedures. (Certain shielded metal-arc and submerged-arc welding procedures, as well as certain types of joints that have had a long record of satisfactory performance, have been granted a prequalified status.) The fabricator depended on submerged-arc welding for the major portion of in-plant production welding, and chiefly on shielded metal-arc welding for welding that was done in the field. Self-shielding flux-cored arc welding was considered to be more economical for some of the field welding. Because neither the flux-cored arc process nor the proposed joint design had a prequalified status, procedure qualification was necessary for the welding to comply with AWS D1.0.

Of the many details specified in the AWS code, the principal requirements of the qualification procedure are: (*a*) to use approved base metals and filler metals; (*b*) to specify the design details of the joint; (*c*) to define the welding process and all welding conditions, such as machine settings, welding position, preheat, speed, techniques, and number of passes used; and (*d*) to perform a prescribed type and number of tests on welded joints, and to meet the acceptance criteria established for the tests. The code also defines the extent of deviations from a welding procedure for which additional qualification tests would be required. Usually, several qualification tests were needed to cover a range of welding conditions. The procedure qualification, which was only one of such tests, is described in the next five paragraphs.

Base Metals. Two approved base metals, ASTM A572, grade 50 (a high-strength low-alloy structural steel with 50,000-psi minimum yield strength), and ASTM A36 (a carbon structural steel with 36,000-psi minimum yield strength), were used to show the capability of the process for welding structural steels. Tensile strength of the joint was expected to equal or surpass the nominal tensile strength of the weaker joint member, which was the A36 steel (58,000 to 80,000-psi tensile strength).

Filler Metal. The flux-cored wire was a proprietary composition for which the mechanical properties of the deposited weld metal were as follows:

Tensile strength	90,000 to 100,000 psi
Yield strength	60,000 to 65,000 psi
Elongation	17 to 20%

This 0.120-in.-diam wire was similar to AWS E70T-4, except that the elongation requirement of the latter is 22%, and the closest wire size in which it is available is ⅛ in. in diameter.

Joint Design. The single-bevel butt joint with backing strip shown in Fig. 20 was designed for economy. The cross-sectional area of this joint was 0.664 sq in. The comparative savings in deposited weld metal for this joint over the prequalified designs for the same type of joint for submerged-arc welding (0.989 sq in.) and shielded metal-arc welding (0.864 sq in.) were about 110 lb per 100 feet of weld (submerged-arc) and 70 lb per 100 feet of weld (shielded metal-arc). In addition, the proposed joint re-

quired only one edge to be beveled, whereas the other processes required both plate edges to be beveled. Access to the smaller groove in flux-cored arc welding was possible because of the small wire diameter and nozzle tip, and the use of a visible wire stickout of 1¼ in.

The procedure was qualified with a 1-in.-thick joint. Qualification for greater thicknesses was obtained by proportionately increasing the number of passes. The backing strip was attached by tack welding.

Welding Conditions and Techniques. Welding was qualified for the flat position, under the welding conditions shown in the table with Fig. 20. Edge preparation was by machining, but gas cutting was permitted. Joint edges were cleaned of oil, grease, excessive amounts of moisture, scale, rust and other foreign material, in accordance with the preweld cleaning requirements. Preheat temperature for the base metals selected was 70 F in the thickness range of ¾ to 1 in. No postheat was required. Welds were deposited using stringer-bead technique, and maintaining the visible stickout at 1¼ in. To obtain adequate penetration with the 0.120-in.-diam electrode, two root beads were used. Five additional passes were needed to fill the joint (Fig. 20). Slag was carefully removed after each pass.

Test Requirements. The length of the test plate (see Fig. 20) was determined by the number of tests required by the code. In this case, two tests for the tensile strength of reduced sections and four side-bend tests were specified. The fabricator chose to add two free-bend tests to determine bend elongation (not to be confused with elongation values obtained in tension tests).

The results of all tests (see table with Fig. 20) met required acceptance criteria.

Example 213. Procedure for Welding Components of a 25-Ton Jackslide (Fig. 21)

The jackslide shown in Fig. 21 weighed 25 tons and was designed to resist the thrust of the main hydraulic jack on a large dragline excavator. One of four such weldments produced, this jackslide consisted of: (*a*) a 44-in.-diam ball-end stanchion forged from a single billet of 8620 steel, (*b*) 3-in. and 5½-in.-thick stiffener plates made of hot rolled ASTM A36 structural steel containing 0.29% carbon max and 0.85 to 1.20% manganese, (*c*) a 5½-in.-thick base plate of A36 steel, and (*d*) end plates and cover plates, also of A36 steel, which boxed in the stiffener ends and formed continuous platforms to the right and left of the main stiffeners. (The cover and end plates have been omitted from Fig. 21.)

The ball-end stanchion had a 10-in.-diam hollow core that extended from the center of the ball to about 3½ in. from the base plate, where the core diameter increased to about 32 in. to produce a 6-in. wall. A single circumferential J-groove weld (not shown in Fig. 21) joined this wall to the base plate.

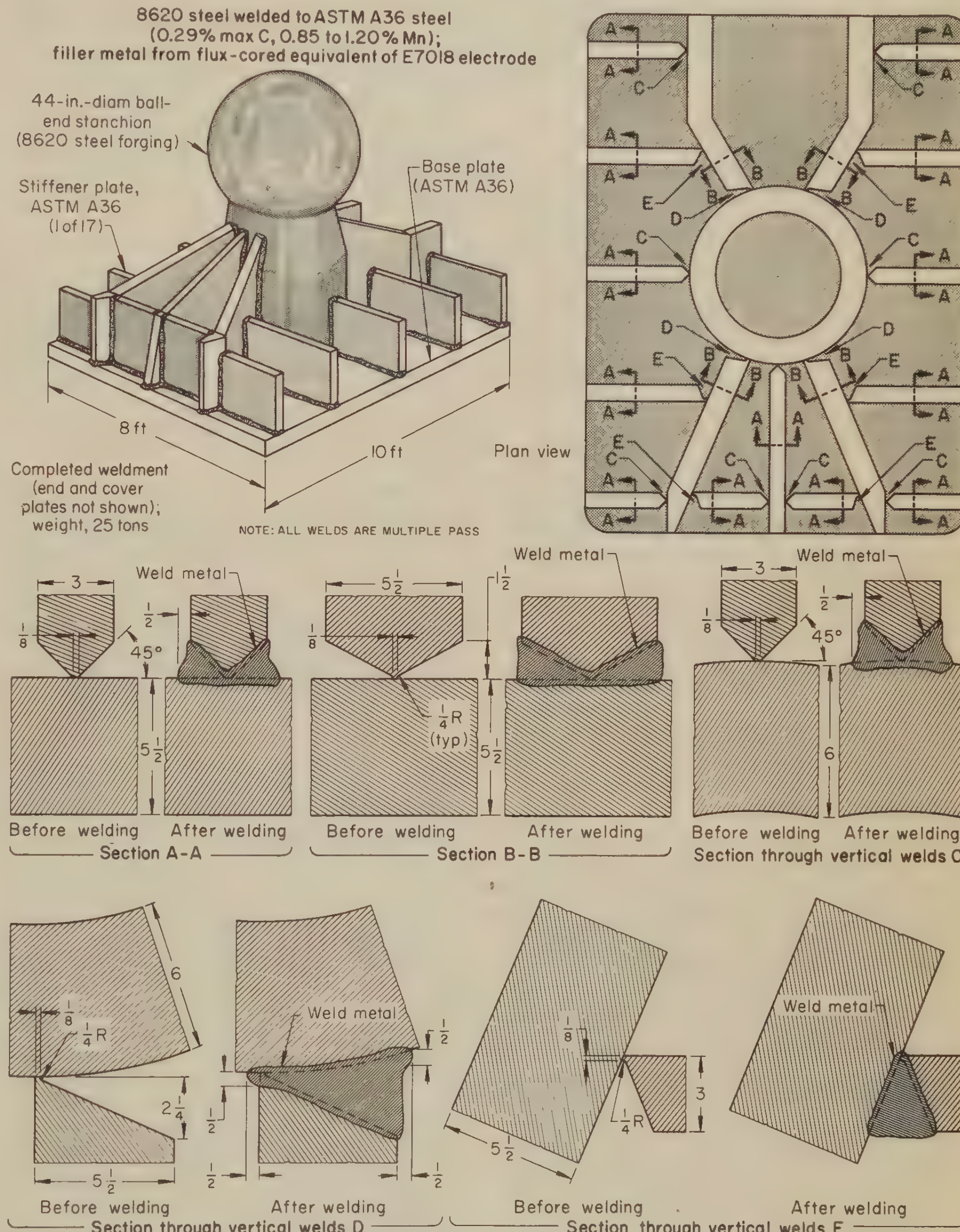
All other joints between components of the assembly were either right-angle or oblique T-joints, and the welds were multiple-pass, full-penetration groove welds. The stems of the T's were either 3 or 5½ in. thick. Edge preparation for the right-angle T-joints in 3-in.-thick material consisted of gas cutting double bevels, each of 45°, on the stem of the T. All other T-joints were prepared by planing single-J or double-J grooves. Typical double-bevel and single-J-groove joints, before and after welding, are shown in Fig. 21.

Welding was done by semiautomatic flux-cored arc welding with carbon dioxide shielding, in the flat and horizontal positions (see table with Fig. 21 for welding conditions). Lifting lugs, 2 in. thick, were full-penetration welded and fitted with clevises for positioning the assembly, which was done by a crane.

The first step was to tack weld the ball-end stanchion to the base plate and heat this assembly to 400 F in a furnace. This joint was then welded without stopping, under continuous heat maintained by torches located under the base plate. Next, all stiffeners were securely tack welded in place, and the assembly was stress relieved by heating in a furnace to 1115 F in 12 hr, holding at temperature for 12 hr, and furnace cooling to 600 F before it was removed and allowed to cool in air. The weld joining the stanchion to the base plate was inspected, and repaired where necessary.

After again preheating to 400 F, all the stiffeners were welded, working two welders per shift, 24 hours a day for 7 days to completion. All surfaces except those being welded were insulated with asbestos blankets. The assembly was again stress relieved, using the same cycle as for the first stress-relief treatment. After the welds were carefully inspected and repaired, the end and cover plates were fitted and welded. The completed weldment was given a third stress-relief treatment, inspected and repaired before machining.

The major hazard in welding the assembly was the danger of weld or underbead cracking, which could be caused by the presence of hydrogen, or caused by shrink-

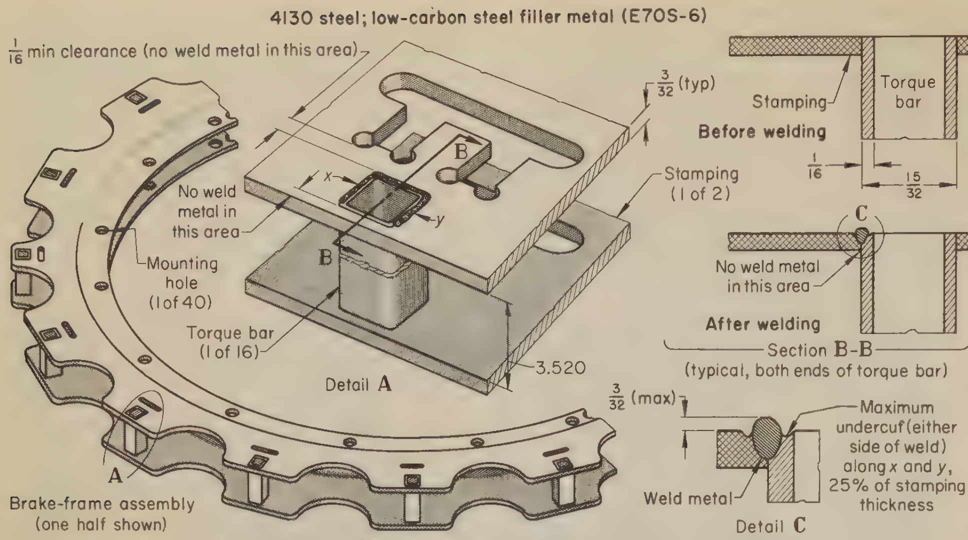


Conditions for Flux-Cored Arc Welding

Joint type	T
Weld types	Double-bevel, single and double J grooves
Welding positions	Flat, horizontal
Edge preparation	Double-bevel grooves, gas cut; J grooves, planed
Preheat	400 F
Postheat (stress relief)	(a)
Shielding gas	Carbon dioxide(b)
Electrode	$\frac{3}{32}$-in.-diam flux-cored equivalent of E7018 flux-covered electrode
Electrode holder	600 amp, water cooled
Wire-feed rate	180 to 200 ipm(c)
Electrode stickout	1¼ in.
Power supply	750-amp constant-voltage rectifier
Current	450 to 500 amp, dcrp
Voltage	32 v

(a) Heat in a furnace to 1115 F in 12 hr, hold 12 hr, furnace cool to 600 F, and air cool to room temperature. (b) At 30 to 35 cfh, from bulk storage, at −45 F dew point. (c) Wire feeder was variable-speed push-pull type.

Fig. 21. Jackslide for a large dragline; plan view showing arrangement of stiffeners that were welded to base plate, to other stiffeners, and to ball-end stanchion; and joint designs (Example 213)



Conditions for Gas Metal-Arc Welding

Joint type	Corner	Electrode	0.035-in.-diam E70S-6
Weld type	Square groove	Electrode holder	Hand held, air cooled
Welding position	Flat	Shielding gas	Carbon dioxide, at 20 cfh
Number of passes	One	Power supply	300-amp constant-voltage motor-generator
Preheat	None		
Postheat (stress relief)	1250 F for 15 min	Current and voltage	90 amp (dcrp); 18 v
Fixture	Assembly jig	Travel speed	4.1 in. per minute

Fig. 22. Brake-frame assembly (one half shown) that was gas metal-arc welded using the short-circuiting mode of metal transfer for close control of deposition (Example 214)

age stress resulting from the number of massive welds made under high restraint. For this reason, the sequence of preheating, fitting, welding and stress relieving was a critical factor.

The initial plan was to preheat, assemble and weld all components except the cover plates. The welds were then to receive a magnetic-particle inspection, be repaired, and the entire assembly stress relieved before the cover plates were added. However, because preheat had to be maintained to the time of stress relief to avoid cracking, it would have been impractical to inspect the welds. Therefore, the weldment received a full stress-relief treatment before each inspection was made.

Gas Metal-Arc Welding

Most of the alloy steels discussed in this article can be welded successfully by the gas metal-arc process. Advantages of this process for the welding of alloy steel are generally the same as for the welding of plain low-carbon steel (see the article on Gas Metal-Arc Welding, which begins on page 78). In some applications, gas metal-arc welding is preferred over other metal-arc processes for alloy steel because of the various modes of metal transfer (spray, globular, short-circuiting, pulsed) that can be obtained and closely controlled.

Two specific advantages of the gas metal-arc process for welding alloy steel are: (*a*) several standardized electrode wires (filler metals) are available (for instance, E70S-1B); and (*b*) extremely small-diameter electrode wire is available. Small-diameter wire helps to deposit a small bead, which is often required in welding alloy steel.

Limitations of gas metal-arc welding compared with shielded metal-arc welding are essentially the same for welding alloy steel as for welding plain low-carbon steel — namely, equipment cost is relatively high, the process is largely restricted to use at nondrafty sites, and equipment is less portable.

Shielding Gas. Factors influencing the selection of shielding gas for welding alloy steel include: base-metal composition, filler-metal composition, mode of metal transfer, welding position, and required quality level. There is no uniformity of practice in regard to gas selection, as is reflected in the eight examples of gas metal-arc welding in this article, in which four different shielding gases (or gas mixtures) were used: carbon dioxide, three examples; 98% argon with 2% oxygen, two; argon, two; and 85% argon with 15% helium, one.

Established practice in a given shop is an important factor in gas selection. For instance, in a shop where most welding is done on low-carbon steel and the available gas is carbon dioxide, every effort will be made to utilize the same shielding gas for welding alloy steel, to avoid installing a separate system. In another shop, where most of the welding is on stainless steel, for which the shielding gas would probably be argon or an argon mixture, the same gas would be utilized for welding of alloy steel. If the amount of welding being done on alloy steel is relatively small, using the available gas will be much more economical than installing a separate system.

Carbon dioxide, because of its low cost, is the most widely used shielding gas for gas metal-arc welding of low-carbon steel, and is also used to a considerable extent for welding of low-alloy steel (see Examples 214, 215 and 217). However, carbon dioxide results in a heat pattern different from that obtained with argon or argon mixtures. Other conditions being the same, greater heat input is obtained with carbon dioxide shielding. This can increase the probability of weld cracking. Sometimes the electrode can be changed to permit carbon dioxide shielding (see Example 215). For welding of low-alloy steel (carbon and alloy content no higher than that of 4130), and when other welding conditions such as section thickness and type of joint are favorable, carbon dioxide is usually suitable as a shielding gas. Since carbon dioxide is an oxidizing gas, the electrode wire must contain greater amounts of deoxidizers such as silicon and aluminum than are required for argon-base shielding gases. In any application, the required weld quality must be considered. For welding of steels having higher hardenability than 4130, carbon dioxide shielding is usually considered unsuitable.

Argon mixtures that include 98% argon and 2% oxygen are extensively used (see Examples 205 and 216) for a variety of different alloy steels. The mixture of 75% argon and 25% carbon dioxide has also been used successfully for welding various alloy steels. Argon-base shielding gases cost more than carbon dioxide, but they provide a more favorable heat input and higher-quality welds.

An all-argon shielding gas is less often used for welding alloy steel, because of weld-bead undercutting, although there are exceptions (see Examples 197 and 219).

Helium costs about 2½ to 10 times as much per cubic foot as argon, depending on the locality and the form and quantity of purchase. An all-helium gas is never used for gas metal-arc welding of alloy steel, and only in relatively few applications is helium used as a component of a shielding-gas mixture. Helium provides a higher heat input than argon, which is sometimes desired. In welding the higher-alloy steels, helium is sometimes mixed with argon (see Example 218, in which a mixture of 85% argon and 15% helium was used for shielding gas in welding of a special tank). Two other mixtures that are sometimes used are: 70% argon and 30% helium (which has the same density as air), and 75% argon and 25% helium.

The mode of metal transfer may influence the choice of shielding gas (see the section on Arc Characteristics on page 79 in the article on Gas Metal-Arc Welding). If it is desired to use the spray-arc mode of transfer, carbon dioxide shielding cannot be used, because a true spray arc does not exist in carbon dioxide. Therefore, argon-base shielding gases are required for the spray-arc mode of transfer (including the pulsed-arc mode). With short-circuiting transfer, either carbon dioxide or an argon-base gas can be used.

Production Examples. The six examples that follow describe techniques that were used for gas metal-arc welding of several alloy steels under various conditions and to meet various requirements (see also Examples 197 and 205).

Example 214. Use of Short-Circuiting Mode of Transfer for Close Control of Deposition in Welding 4130 Steel (Fig. 22)

A brake frame, half of which is shown in Fig. 22, was a welded assembly of two 4130 steel frame pieces (stampings) and sixteen 4130 steel torque bars (extrusions), joined by the gas metal-arc process. Forty mounting holes (20 opposing pairs) had to be held in accurate alignment, and each weld had to be closely controlled for bead

size and shape, weld-metal flow, and joint penetration. It was required that surfaces and edges as designated in Fig. 22 be free from weld metal and that undercutting along two sides of each weld (see detail C in Fig. 22) not exceed 25% of the stamping thickness. Porosity was limited to a maximum of three pinholes in any one continuous weld, with a maximum pinhole diameter of 1/32 in. The close control necessary for compliance with these requirements was achieved with the short-circuiting mode of metal transfer.

The stampings and torque bars were assembled in a welding fixture, with a tension bar (not shown in Fig. 22) tack welded to each frame half to maintain alignment of the mounting holes. The joints were then welded by the semiautomatic gas metal-arc process, under the conditions tabulated with Fig. 22. Each of the 16 joints on one side of the assembly was welded on three sides in the flat position (detail A in Fig. 22). Then the assembly was inverted and the process was repeated on the reverse side.

After welding, the assembly was removed from the fixture and stress relieved at 1250 F for 15 min. On cooling to room temperature, the tension bar was removed, and the tack weld was ground off. Finally, the assembly was shot peened.

Example 215. Selection of Filler Metal To Attain 100% Penetration Without Cracking in Welding 4130 Steel Rings (Fig. 23)

Cargo tie-down rings were fabricated from 4130 steel rods that ranged from 1/2 to 7/8 in. in diameter. Cut to length with a standard rod cutter, the rods were formed into rings 3 to 8 in. in outside diameter and welded, using the semiautomatic gas metal-arc process under the conditions in the table with Fig. 23. Because the rod cutter produced beveled ends, as shown in Fig. 23, no further joint-edge preparation was necessary.

Weld requirements included 100% joint penetration, and freedom from defects detectable by magnetic-particle inspection. No preheating or postweld stress relieving was used, although welded rings were quenched and tempered for strength and toughness.

For economy and speed of production, a three-pass weld sequence was developed, as follows:

1 Penetrate through the root on one side of the ring with the first pass.
2 Turn the ring to the reverse side and, without back grinding, fill this side of the joint in one pass.
3 Reverse the ring to its first position and complete the weld with the third pass (see Fig. 23).

Selection of a suitable combination of electrode wire and shielding gas was difficult. At first, a 4130 steel electrode wire was used with argon, or a mixture of argon and carbon dioxide, as the shielding gas. Full penetration could not be obtained with either of these shielding gases. By changing to a 100% carbon dioxide shielding gas, full penetration was obtained. With all three shielding gases, however, cracks were found after heat treatment. Cracking was prevented without the need for preheating by replacing the 4130 steel electrode wire with a low-carbon, low-alloy wire having the composition shown in the table with Fig. 23. With this electrode wire and carbon dioxide shielding, full penetration was also obtained.

Sample sectioning was used to verify full penetration, and freedom from cracks was ensured by 100% magnetic-particle inspection. Tension tests made after heat treatment of joints welded with the low-carbon, low-alloy electrode wire ensured that joint strength was sufficient.

Example 216. Change From Shielded Metal-Arc to Gas Metal-Arc Welding To Eliminate Cleaning and Reduce Cost (Fig. 24)

Water-wall panels, for later installation adjacent to burner openings in power boilers, were fabricated by welding a series of tubes made of 1.25 Cr, 0.5 Mo steel (ASTM A213, grade T11, 0.15 C max) to fins of the same material. Figure 24 shows a portion of a typical panel assembly, and the joint and weld details. Joint-groove preparation was not required. The 1/8 to 5/32-in. fillet welds produced the desired partial joint penetration.

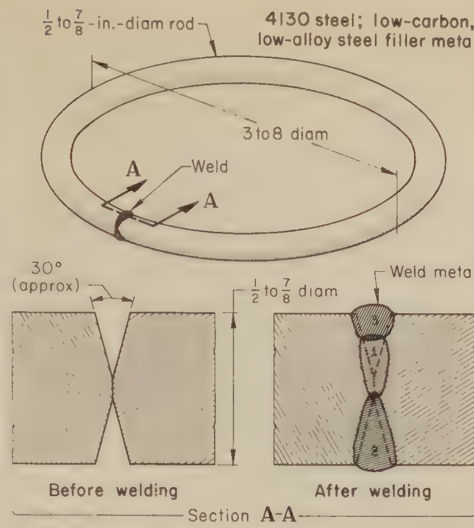
Originally, the panels were welded by the shielded metal-arc process, which produced welds with acceptable properties, but a slag-removal operation was required and the process was considered slow.

Gas metal-arc welding also produced welds of the required quality, and in addition, eliminated the need for removing slag, and more than doubled the welding speed. Welding cost per foot was reduced from $0.825, for shielded metal-arc welding, to $0.225, for gas metal-arc. Welding conditions for both processes, together with a comparison of costs per foot of weld, are presented in the table with Fig. 24.

Often, preheating or postheating, or both, are required when welding this steel. In this application, however, a combination of favorable conditions resulted in the production of sound welds without preheat (only to 60 F if needed) or postheat treatment. One of these conditions was weldment design; because section thicknesses were relatively uniform, and, more important, because the four single-pass welds were close to each other, the entire weldment was heated considerably (up to 500 F) during welding, thus providing the effect of preheating and postheating. A second favorable condition was that the gas metal-arc welding was done with the pulsed-arc mode of metal transfer. This type of welding current was used because it produced spray-type metal transfer at a lower heat input than was obtained by conventional spray-arc transfer. A third favorable condition was that the 98% argon, 2% oxygen shielding gas used in gas metal-arc welding resulted in a heat input that was less likely to cause cracking than the much greater heat input that results from shielding with carbon dioxide.

The tubes were precleaned by belt sanding and the fins were cleaned by shot blasting. Tack welding was used in making the assembly.

The shielded metal-arc process that had been used for this application was, therefore, superseded by the more economical gas metal-arc process. Welds made by both processes were tested in accordance with requirements of the ASME boiler code: two reduced-section tension tests, two root bends, and two face bends.

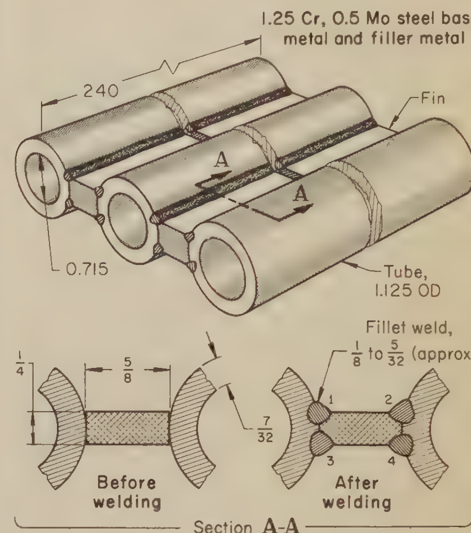


Conditions for Gas Metal-Arc Welding

Joint type	Butt
Weld type	Double-V groove
Welding position	Flat
Number of passes	Three
Preheat or postweld stress relief	None(a)
Shielding gas	Carbon dioxide, at 20 cfh
Electrode wire	0.035-in.-diam low-alloy steel(b)
Electrode holder	Hand held, air cooled
Wire feed	Constant-speed type
Power supply	300-amp constant-voltage rectifier, with slope control
Current	150 amp, dcrp
Voltage	20 v

(a) Welded rings were quenched and tempered for strength. (b) Composition: 0.11 to 0.17 C, 1.75 to 2.10 Mn, 0.65 to 0.85 Si, 0.40 to 0.60 Mo, 0.15 max Ni.

Fig. 23. Tie-down ring, gas metal-arc welded without preheat or postweld stress relief, for which 100% joint penetration without cracking was obtained by use of a low-carbon, low-alloy filler metal and carbon dioxide shielding (Example 215)



Conditions Common to Both Processes

Joint type	T
Weld type	Fillet
Welding position	Flat
Number of passes	One
Preheat	None (except to 60 F, if required)
Postheat treatment	None

Conditions for Shielded Metal-Arc Welding

Electrode	5/32-in.-diam E8018-B2L
Current	170 to 195 amp, dcrp
Voltage	23 v
Welding speed (approx)	12 in. per minute
Deposition efficiency(a)	50%
Operating factor(b)	0.20

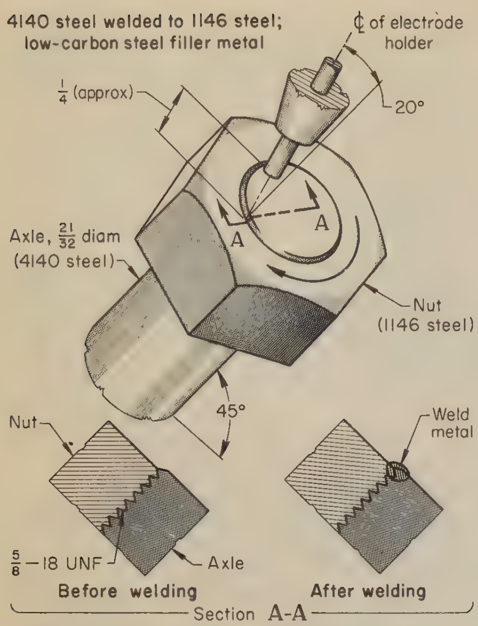
Conditions for Gas Metal-Arc Welding

Power supply	300-amp constant-voltage transformer-rectifier with half-wave rectified pulser
Electrode holder	200 amp, not water cooled
Wire feed	Push type, dial control
Shielding gas	98% argon – 2% oxygen, at 35 cfh
Electrode wire	0.035-in.-diam 1.25 Cr, 0.50 Mo steel
Current	170 amp, dcrp (pulsed)(c)
Voltage	23 v
Welding speed	30 in. per minute
Deposition efficiency(a)	95%
Operating factor(b)	0.40

Item	Shielded metal-arc	Gas metal-arc
Comparison of Costs per Foot of Weld		
Electrode cost	$0.075	$0.052
Gas cost	...	0.023
Manufacturing cost(d)	0.750	0.150
Total(e)	$0.825	$0.225

(a) Weight of weld deposit divided by weight of electrodes consumed. (b) Arc time divided by operator time. (c) Value represents average peak pulse. (d) Labor and overhead. (e) Includes cost of cleaning.

Fig. 24. Portion of a water-wall panel, of heat-resisting steel, that, although successfully welded by both processes without preheating or postheat treatment, cost less to weld by gas metal-arc than by shielded metal-arc (Example 216)



Conditions for Automatic Gas Metal-Arc Welding

Joint type	Circumferential butt
Weld type	Square groove
Number of passes	One
Preheat and postheat	None
Shielding gas	Carbon dioxide(a)
Electrode wire	0.035-in.-diam low-carbon steel
Electrode holder	Machine held, air cooled
Wire-feed rate	264 in. per minute
Power supply	250-amp constant-voltage transformer-rectifier
Current	160 amp, dcrp
Voltage	19 v
Travel speed	16.8 in. per minute
Production rate	115 assemblies per hour(b)

(a) Supplied from cylinder, at 5 to 10 psi. (b) In semiautomatic method, production rate was 59 assemblies per hour.

Fig. 25. Axle assembly for which change from semiautomatic to automatic gas metal-arc welding increased production rate and improved appearance of weld (Example 217)

Example 217. Change From Semiautomatic to Automatic Gas Metal-Arc Welding of Axle Assemblies (Fig. 25)

The rear-wheel axle assembly shown in Fig. 25 was originally welded by the semiautomatic gas metal-arc process at a rate of 59 assemblies per hour. A change to automatic gas metal-arc welding increased production to 115 assemblies per hour; also, less skill was required for the welding operation, and all welds had a more uniform appearance.

The axle was made of 4140 steel, strain hardened to approximately 125,000-psi yield strength. The nut was made of a killed 1146 free-cutting steel. Although this steel is not recommended for welding, the free-cutting additives produced no noticeable detrimental effects.

Before being welded, the axle and nut were degreased and assembled. The assembly was manually loaded in a special chucking fixture, and the axle, at 45° to the horizontal, was rotated clockwise, at 16.8 in. per minute at the joint. Welding was fully automatic, and the electrode holder was held in a retractable air-operated mechanism. The holder was air cooled. No preheating or postheating was needed, and the weld was made in one pass.

Since the purpose of the weld was to fix the nut permanently to the axle, penetration through at least one thread engagement (see Fig. 25) was required. This penetration was obtained by welding under the conditions listed in the table with Fig. 25.

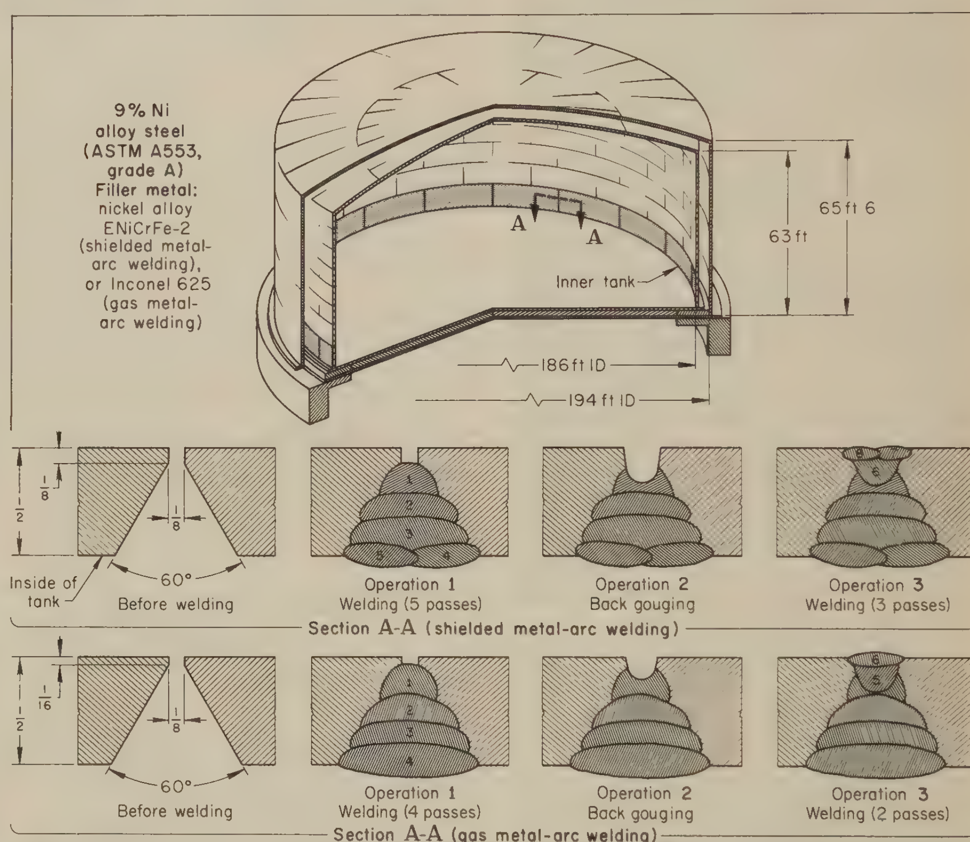
After being welded, the axle assembly was washed, zinc plated, and heated for 3 hr at 375 ± 25 F. This heat treatment served to lessen danger of hydrogen embrittlement resulting from the plating operation. The welds were inspected visually.

Example 218. Costs and Procedures for Shielded Metal-Arc vs Gas Metal-Arc Welding of 9% Nickel Steel Storage Tanks (Fig. 26)

A cost comparison, based on production records, was made between shielded metal-arc welding and pulsed-current automatic gas metal-arc welding of vertical joints in large field-erected tanks used for storing liquefied natural gas. Figure 26 shows the double-wall construction of a typical tank and details of the vertical joints of the 290,000-bbl inner tank for which the comparison was made. Welding conditions and cost data are given in the table accompanying Fig. 26.

The inner tank was fabricated of a 9% nickel steel (ASTM A553, grade A), which provided the required low-temperature strength properties at a reasonable cost. Although the welding procedures of the two processes differed in detail, each produced welded joints that met the required minimums of 95,000-psi tensile strength and 52,500-psi yield strength. Charpy V-notch impact values greater than 20 ft-lb at −320 F in the weld and in the heat-affected zone were also required. Design and fabrication were in accordance with API Standard 620, Appendix Q, for low-pressure liquefied natural gas storage tanks.

The inner tank was constructed of eight courses, or rings. The bottom course was made of ½-in.-thick plates, the second course of 0.44-in.-thick plates, and the six successive courses were made of ⅜-in.-thick plates. The cost comparison was made on the basis of welding the 19 vertical joints in the ½-in.-thick bottom course. Details of bottom-course joints welded by the two processes are shown in section A-A in Fig. 26.



Item	Shielded metal-arc welding	Automatic gas metal-arc welding
Comparison of Welding Conditions		
Number of passes	Eight	Six
Shielding gas	...	85% argon – 15% helium, at 35 cfh
Electrode wire	⅛-in.-diam ENiCrFe-2	Inconel 625(a)
Power supply	300-amp rectifier	300-amp rectifier, with half-wave rectifier pulser
Current	Passes 1, 2, 3, 6(b): 50-80 amp, dcrp; Passes 4, 5, 7, 8(c): 60-90 amp, dcrp	All passes(c): 90-130 amp, dcrp(d)
Voltage	22 to 26 v	18 to 23 v
Auxiliary equipment	None	Automatic travel, wire feeder, and oscillator
Travel speed	No estimate	4 to 7 in. per minute
Comparison of Costs per Foot of Weld		
Labor and overhead(e)	$38.36	$16.21
Materials	6.75	9.87
Total cost	$45.11	$26.08
Repair rate allowed	20%	10%(f)

(a) Modified composition: 0.1 C, 0.5 Mn, 0.5 Si, 21.5 Cr, 9.0 Mo, 5.0 Fe, 1.0 Co, 0.4 Al, 0.4 Ti, rem Ni. (b) Vertical up. (c) Vertical down. (d) Half-wave-rectified (60-cycle) pulsed current, superimposed on a dc background current. (e) At $14 per hour, including operator factor, but excluding edge preparation and assembly. (f) Actual repair rate was less than 1%.

Fig. 26. Cutaway view of a double-wall tank used for storing liquefied natural gas. Welding conditions and costs data in table are for the bottom course of the inner tank, which was selected as typical and as a basis for comparing procedures and costs. (Example 218)

The table with Fig. 26 omits the operations that were the same for both processes. These included beveling of plate edges by gas cutting, the wire brushing and grinding of joint surfaces, plate fit-up, and plate inspection. Plates were not preheated, but if the temperature fell below 32 F, the steel was heated so that it was warm to the touch. No postheating was used.

One of the difficulties encountered during welding was arc blow, which resulted from the relatively high magnetic permeance and remanence of the 9% nickel steel. Pulsed-current gas metal-arc welding could be done in magnetic fields up to 100 gausses, but the maximum field for shielded metal-arc welding was 50 gausses.

For shielded metal-arc welding, as shown in Fig. 26, eight passes were required. The root pass (1) and the three filler passes (2, 3 and 6) were made vertical up, and the relatively wide and thin cover passes (4, 5, 7 and 8) were made vertical down. Thorough slag removal between passes was essential in order to obtain the high-quality welds that were required by the 100% radiographic inspection.

Only six passes were required for gas metal-arc welding (Fig. 26); all passes were made vertical down. For the root pass (1), the electrode holder was guided manually. For the remaining passes, the electrode holder was mounted on a variable oscillator, which, in turn, was mounted on a carriage for automatic travel. The electrode holder was oscillated for passes 2 through 6. In addition to these features, the power supplied for welding was of the pulsed type, which provided uniform spray transfer of filler metal, low heat input and greater resistance to arc blow.

The automatic gas metal-arc process was not only faster, by permitting the weld to be made in fewer passes, but also reduced repair costs and produced welds of higher quality. The actual repair rate was less than 1%; that is, after radiographic inspection, less than 1 in. out of 100 in. of weld required chip-out and rewelding. The repair rate for shielded metal-arc welding varied considerably among individual welders and averaged about 20%.

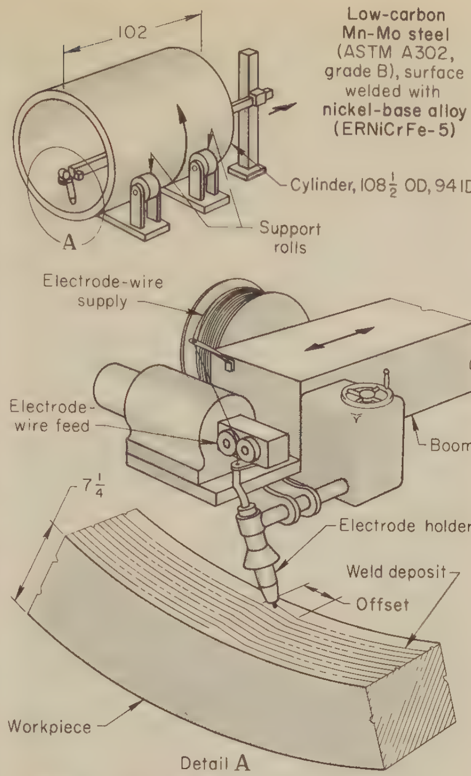
These process and quality differences are reflected in the lower cost per foot of weld for gas metal-arc welding (see table with Fig. 26). The major disadvantages of gas metal-arc welding were the higher equipment costs and the need to shield the operation from drafts.

Example 219. Surfacing a Low-Carbon Mn-Mo Steel Cylinder With a Nickel-Base Alloy (Fig. 27)

The 7¼-in.-wall cylinder shown in Fig. 27 was fabricated from quenched and tempered low-carbon Mn-Mo steel plate (ASTM A302, grade B). It was required that the inside of the cylinder be surfaced with a high-quality deposit from ERNiCrFe-5 electrode wire (a nickel-base alloy wire with a composition similar to that of Inconel 600) to meet rigorous requirements for chemical and mechanical properties.

Gas metal-arc surfacing was done with automatic welding equipment, which was mounted on a manipulator boom and placed inside the cylinder in a manner that permitted it to traverse the length of the cylinder (see Fig. 27). The cylinder was placed on support rolls, and was rotated by variable-speed drive rolls that provided a rotational speed corresponding to the speed desired for weld deposition. The design of the welding head provided for constant oscillation of the holder in the direction transverse to that of travel, thereby producing a relatively wide and thin deposit.

During surfacing, the electrode holder was held at a fixed point for each revolution of the cylinder. As completion of each 360° rotation was approached, and without interruption of welding, a timer was actuated and the welding boom was moved longitudinally at a fixed rate and for a fixed distance to provide the desired bead pitch. This sequence was repeated as the electrode holder traversed the length of the cylinder to produce overlapping deposits of uniform dimensions and quality. The offset weld-overlay pattern produced by the operation is shown in detail A in Fig. 27. Additional welding details are given in the table that accompanies Fig. 27.



Conditions for Gas Metal-Arc Surfacing

Power supply	400-amp rectifier, with drooping voltage
Preheat and postheat	None
Electrode wire	0.062-in.-diam ERNiCrFe-5
Shielding gas	Argon
Deposition rate at 100% arc time	11 lb/hr

Fig. 27. Setup and deposition pattern for surfacing the inside of a large steel cylinder (Example 219)

Submerged-Arc Welding

As indicated in Table 10, the submerged-arc process can be used to weld a variety of alloy steels. Advantages of the process for welding alloy steels are, for the most part, the same as for low-carbon steels — high deposition rate and low cost. For welding of alloy steels the high deposition rate may be especially advantageous, because a larger area is heated and thus cooling rate is slower. In addition, the flux used in submerged-arc welding serves as a blanket and retards the cooling rate, and may help to prevent cracking. Consequently, the submerged-arc process is sometimes selected in preference to other arc processes because of the lower risk of weld cracking (see Example 222).

The major limitation of the submerged-arc process for welding alloy steels is the same as for carbon steels — namely, that it restricts the number of welding positions that can be used (see the article on Submerged-Arc Welding, which begins on page 46).

Production Examples. The five examples that follow give details for submerged-arc welding of several different alloy steels (see also Example 207).

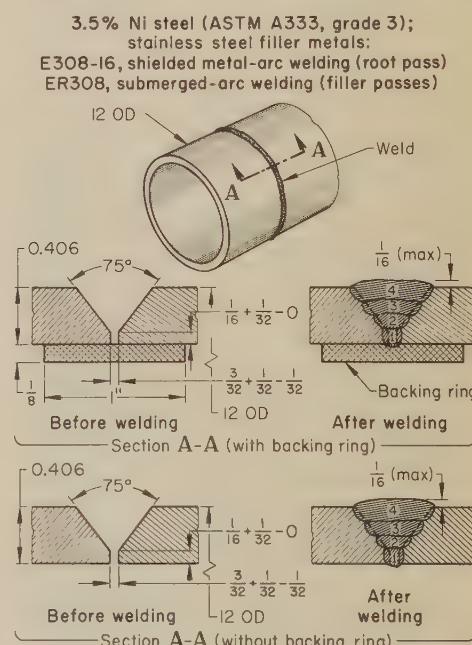
Example 220. Welding 3.5% Nickel Steel Pipe Sections for Low-Temperature Service (Fig. 28)

The pipe shown in Fig. 28 was nickel steel (3.2 to 3.8% Ni) and was welded with stainless steel filler metal to meet the mechanical-property requirements of ASTM A333, grade 3, which included a minimum tensile strength of 65,000 psi and a minimum notched-bar impact value of 15 ft-lb at −150 F (10-mm-by-10-mm specimens).

The joint design shown in Fig. 28 was used for the 0.406-in. wall thickness, as well as for similar pipes having wall thicknesses up to ¾ in. The mechanical-property requirements could be met by welding either with or without backing rings.

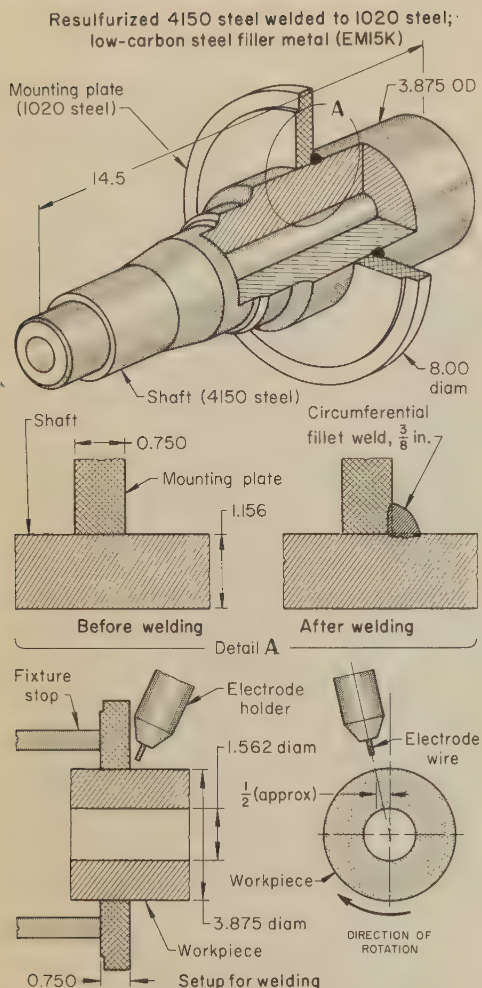
Where service conditions and specifications permitted, backing rings were used (which were allowed to remain in place) to reduce the time and welder skill needed to make the root pass. The root pass was made without a backing ring when internal obstructions were not allowed. Making the root pass required skill to obtain complete fusion of the root with a smooth inside root condition. Care was used with both procedures to ensure full root penetration.

Because it was less costly, automatic submerged-arc welding was used for all passes except the root pass. It was not suitable for the root pass because drop-through would occur if no backing were used, or the welding flux could be trapped between the backing ring and the pipe, which could cause incomplete fusion and other defects. The root pass was made by shielded metal-arc welding with ⅛-in.-diam E308-16 electrodes. This metal was sluggish, requiring the weld puddle to be "pushed" with the arc. A skilled welder could produce a smooth root pass approximately 3/32 in. deep. To guard against cracking, weld starts were made by backstepping over previous deposits. Although no preheat was



Item	Shielded metal-arc welding (root pass)	Automatic submerged-arc welding (filler passes)
Number of passes	One	Three
Electrode wire	E308-16	ER308
Electrode diam, in.	⅛	⅛
Wire feed, ipm	...	15
Current, amp	95-125, dcrp	250, dcsp
Voltage, v	20-24	25
Interpass temp, F	150-350	150-350
Travel speed, ipm	...	12-15

Fig. 28. Circumferential welding of pipe for low-temperature service, showing joint designs for welding with and without a backing ring (Example 220)



Conditions for Submerged-Arc Welding

Joint type	Circumferential T
Weld type	Fillet
Welding position	Horizontal rolled
Number of passes	One
Preheat and postheat	None
Electrode wire	3/32-in.-diam EM15K
Flux	F72
Wire feed (automatic)	156 in. per minute
Electrode stickout	½ in.
Electrode holders	600 amp, fixed position
Power supply	Constant-current rectifier, with slope control
Current	340 amp, dcrp
Voltage	26 v
Electrode consumption	0.3 lb per assembly
Deposition rate	18 lb per hour
Weld overlap	⅜ in.
Welding speed	1.12 rpm
Weld time per assembly	0.993 min
Production rate	33½ assemblies per hour
Postweld finishing	Slag chipped away

Fig. 29. Shaft of resulfurized 4150 steel welded to a 1020 steel plate, showing joint design and setup for welding (Example 221)

used, interpass temperature was held in the range of 150 to 350 F to avoid overheating and subsequent cracking.

Details of both the manual root-pass welding and the automatic submerged-arc welding are given with Fig. 28. Data for root-pass welding with and without backing were not separated because welding current and speed varied with welders and were not accurately predictable.

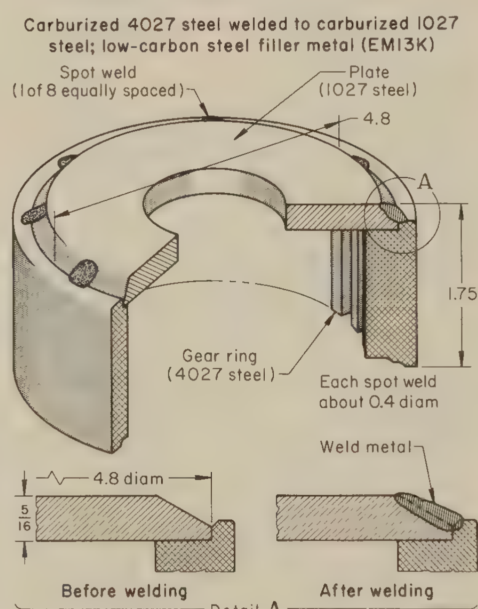
Edge preparation and preweld cleaning, as well as quality-control methods, inspection and testing, were in accordance with the ASME code. Weld surfaces had to be clean of solid matter, oil, and grease. All slag and flux had to be removed before successive beads were deposited. Cracks and blowholes on bead surfaces had to be removed by chipping or grinding. Undercutting was not permitted. Impact values for welds made with and without backing did not differ, provided that the root pass was smooth and uniform. Qualification welds were inspected visually, by radiography, by magnetic-particle or liquid-penetrant methods, and metallographically. Radiographic interpretation was more difficult when backing rings were used.

Essentially the same procedure as that described above was used for welding pipe sections of the following steels: A203, grades D and E; A334, grade 3; A350, grade LF3; and A352, grade LC3.

Example 221. Welding Resulfurized 4150 to 1020 Without Preheat or Postheat (Fig. 29)

The axle for an industrial lift truck consisted of a drive axle shaft welded to a brake mounting plate (Fig. 29). The shaft was machined from a 4-in.-diam bar of resulfurized 4150 steel heat treated to 293 to 352 Bhn, the plate from 1020 steel. After machining, the shaft was fitted to the brake mounting plate for welding. A ⅜-in. fillet weld with 0.100-in. minimum joint penetration was required.

Resulfurized 4150 (0.08 to 0.13% sulfur) was selected for its good machinability because the design of the shaft called for extensive machining. Generally, high-sulfur steels are not selected for parts that are to be welded, since the high sulfur content often causes hot cracking and porosity in the weld. In this application, an electrode-flux combination (EM15K-F72) that prevented excessive porosity was used. Typical composition of the weld deposit produced by this combination was: 0.076% C, 1.54% Mn, 0.79% Si, 0.025% P, and 0.021% S.



Conditions for Submerged-Arc Spot Welding

Joint type	Corner
Weld type	Spot(a)
Welding position	Flat
Joint preparation	Machined, press fit
Preheat and postheat	None
Electrode wire	1/16-in.-diam EM13K(b)
Flux	F62
Electrode holders	Two, air cooled, set in automatic indexing fixture
Electrode stickout	¾ in.
Wire-feed rate	2 in. of wire per weld
Power supply	Two 600-amp constant-voltage transformer-rectifiers
Current	400 amp, dcrp
Voltage	31 to 32 v
Production per machine	150 assemblies/hr

(a) One-spot welds, made two at a time. (b) Single-deoxidized. Initially, a triple-deoxidized electrode wire (E70S-2) had been used.

Fig. 30. Annulus gear assembly welded in the carburized-and-hardened condition by submerged-arc spot welding (Example 222)

Although the welding of 4150 steel normally requires preheating and postheating, neither treatment was used and no cracking occurred. At least two conditions favored successful welding without preheating: (*a*) the blanketing effect of the flux used in the submerged-arc process often provides slow cooling and eliminates the need for preheating, and (*b*) a ductile weld was produced because one component of the weldment was 1020, which has excellent weldability, and the deposited weld metal was of low carbon content.

The assembly was welded with the axis of the hollow shaft in the horizontal position. A mandrel, inserted in the shaft, was held between the headstock and tailstock of a lathe-type rotating positioner. The relatively small diameter of the shaft at the weld, and the fact that the workpiece was rotating (clockwise), required placing the electrode holder ½ in. before the 12 o'clock position (Fig. 29). This placement permitted the molten weld metal and the flux to remain in a near-horizontal position long enough for the metal to solidify before the flux ran off the rotating workpiece. The normal 1-in. stickout was reduced to ½ in. and a flux nozzle with a diameter of ¾ in. was used to obtain a satisfactory flow of flux.

In tests, the welds of the assembly withstood loads of 142,000 to 240,000 lb — equivalent to a tensile strength of 31,000 to 52,000 psi (the minimum tensile strength required was 12,000 psi).

Each weld was inspected visually by the operator. A periodic examination of welds was also made by the line inspector with a fillet gage and by magnetic-particle inspection. There have been no failures of axles in several years of service.

The original cost of the submerged-arc welding equipment used was $18,000.

Example 222. Use of Submerged-Arc Spot Welding To Join Carburized and Hardened 4027 to 1027 (Fig. 30)

The annulus gear assembly shown in Fig. 30 consisted of a forged steel plate that was press-fitted into a cylindrical gear ring and then secured by eight submerged-arc spot welds. Welding conditions are given with Fig. 30.

Originally, these components for an automatic transmission were held together by a high-carbon steel snap ring that fitted into a machined groove in the gear ring. Conversion to welding yielded a saving of $0.256 per assembly.

The 1027 steel plate and 4027 gear ring were carburized, hardened and finish machined before assembly. Welding by gas metal-arc or gas tungsten-arc resulted in cracked gear rings and weak welds, but the submerged-arc spot welding procedure, in which the blanketing action of the flux was used in combination with a deoxidized electrode wire, produced a weld that was sound and ductile.

The welded joint was specified to resist a minimum push-off load of 8000 lb for service applications. The quality of the welds was checked by testing one gear to destruction at the end of each 2-hr production run. Most of the destroyed gears withstood push-off loads of 13,000 to 14,000 lb.

The gear was originally welded with a triple-deoxidized electrode wire at a saving of $0.250 compared with the cost of the gear assembled with the snap ring. It was later found that a single-deoxidized electrode wire could be used satisfactorily; this increased the saving per assembly to $0.256.

Example 223. Selection of Submerged-Arc Welding for High-Quality Welds and High Production Rate (Fig. 31)

The aircraft drive-shaft assembly shown in Fig. 31 was made by pressing a cold drawn 4130 steel tube (3-in. OD by 0.083-in. wall) onto a recess in a 4140 steel gear hub to form a tight, square butt joint. The joint had to be welded in a single pass and with full penetration (see section A-A in Fig. 31). The cold drawn tube had a tensile

strength of 105,000 psi, and the 4140 steel gear hub was quenched and tempered to Rockwell C 32 to 38 before being welded.

Because of the production rate required, only automatic welding processes were considered. In developing a welding procedure, three processes that were readily available were investigated — shielded metal-arc, gas metal-arc, and submerged-arc welding. (The automatic shielded metal-arc process considered is one utilizing a continuous electrode with a light wash coating of flux. Because it affords poor shielding, the process is seldom used.)

The welding conditions for each of the three processes evaluated are given in the table accompanying Fig. 31. For all processes the parts were grit blasted and degreased before press fitting. The assembly was mounted horizontally between the headstock and tailstock of a lathe-type positioner, and a full-penetration weld was made in a single pass. No preheat was used but, after welding, the assemblies were heated to 900 F for 5 min in a furnace to temper the martensite that formed during cooling from the welding temperature.

The three cross sections of welded joints in Fig. 31 show the relative weld configurations, heat-affected zones, and porosity contents obtained by the three processes. The gas metal-arc welds were smallest in size and in heat-affected area but had considerable porosity and an objectionably high weld reinforcement. Fatigue life, under the test described in footnote (e) in the table with Fig. 31, was 6 million cycles, which was acceptable. The shielded metal-arc welds were so full of porosity and had such a high weld reinforcement and generally inferior appearance that fatigue testing was omitted and further investigation of shielded metal-arc welding for this application was discontinued.

Although the submerged-arc welds were the largest in size, the heat-affected zone was intermediate in depth, porosity was completely absent, and the low reinforcement blended smoothly into the base metal. [It may be noted in Fig. 31 that the sizes of the heat-affected zones were approximately proportional to the heat inputs, which were (in joules per inch): 10,700 for gas metal-arc, 13,800 for submerged-arc, and 14,900 for shielded metal-arc.] These factors, as well as higher fatigue life (7 million cycles) and slightly higher production rate compared with gas metal-arc welding, provided the basis for selecting automatic submerged-arc welding.

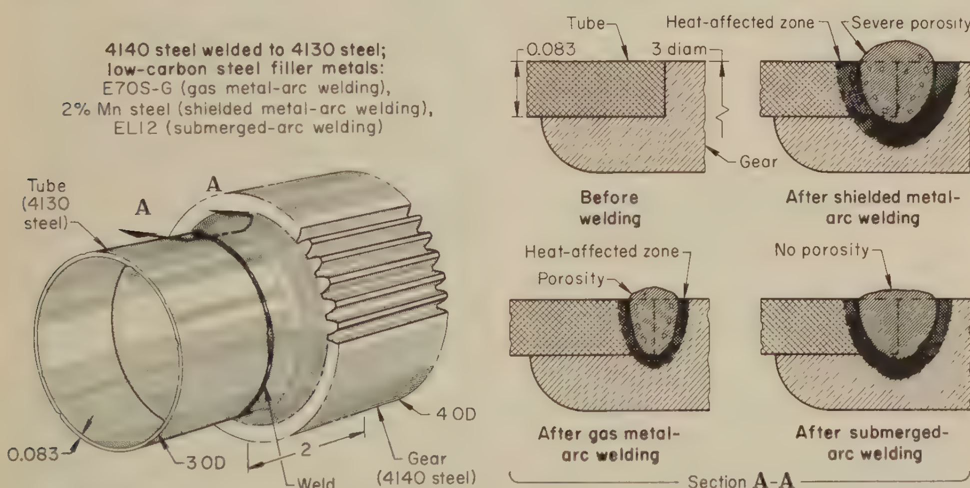
Example 224. Change to Welded Design That Simplified Manufacture of Wheels for Military Tracked Vehicles (Fig. 32)

The production of wheels with special wear rings for use on military tracked vehicles entailed costly operations. As shown in Fig. 32 (original design), the wheel surface subject to wear from contact with the track shoes was protected by a hardened 4130 steel wear ring fixed to the wheel with 18 rivets. Attaching the wear ring was a cumbersome procedure. The ring had to be straightened, after hardening, and carefully fitted, drilled and then riveted. The wheel was formed from a disk of 1025 steel by drawing, annealing, flanging the small outer lip, and restriking for size.

The wear ring was eliminated in an improved design of the wheel (see top and bottom views in Fig. 32). By making the wheel from a disk of 4130 steel or a high-strength structural steel, the area subject to wear could be induction hardened to a depth of ⅛ in. minimum (287 to 461 Bhn). This design entailed a welded reinforcing ring being substituted for the flanged outer lip, because the higher-strength steel could not be formed to the ⅜-in. bend radius of the flange. The reinforcing ring could be made of any carbon steel from 1008 to 1025.

Procedures for welding the reinforcing ring varied with wheel size, thickness and production requirements. The joint, as shown at lower right in Fig. 32, was designed for a full-penetration groove weld with a fillet-weld reinforcement of approximately ⅜ in. After fitting and tack welding of the ring, the wheel was mounted on a rotating fixture, which was inclined to permit welding in essentially the flat position, and the weld was made in a single pass, after which the weldments were rolled along a chute to the induction heating station. Welding conditions are given in the table accompanying Fig. 32.

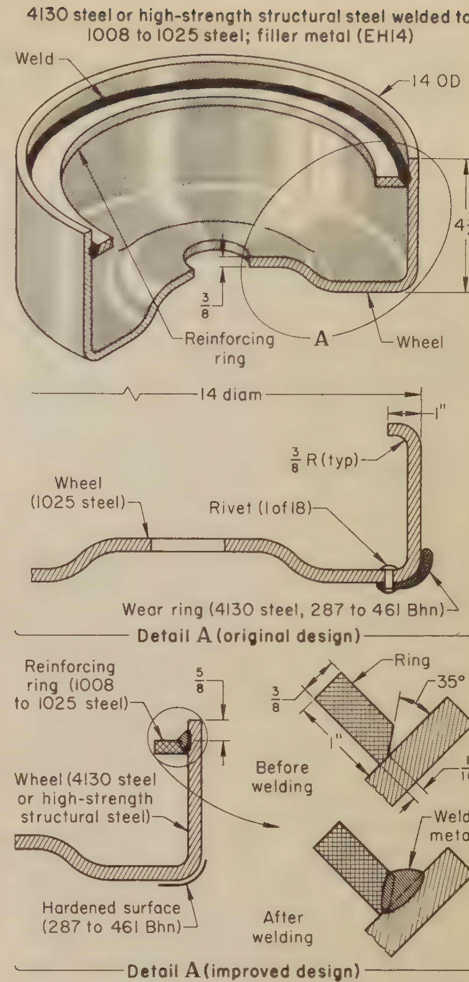
Finished welds were inspected visually for general appearance, surface defects, and size. Visible defects were repaired by grinding and rewelding. One piece per shift (a minimum of two pieces per setup) was



Item	Automatic shielded metal-arc welding	Automatic gas metal-arc welding(a)	Automatic submerged-arc welding
Welding Conditions(b)			
Electrode wire	(c)	E70S-G	EL12
Electrode diameter, in.	⅛	0.045	⅛
Flux	(d)	None	F71
Rating of motor-generator, amp	300	300	600
Current (dcrp), amp	180	240	315
Voltage, v	18	26	27
Heat input, joules per inch	14,900	10,700	13,800
Travel speed, in. per minute	13	35	37
Test Results			
Porosity	Severe	Considerable	None
Weld hardness, Rockwell C	30 to 34	45 to 51	49
Fatigue life, cycles(e)	(f)	6 million	7 million
Production, assemblies per hour	25	70	75

(a) Carbon dioxide shielding. (b) For welding conditions that were the same for all three processes, see the text. (c) A solid 2% Mn low-carbon steel electrode (unclassified) supplied in coils. (d) A light wash coating on the electrode wire, to permit automatic feeding. (e) Shafts tested in torsion under loads of 30,000 to 45,000 in.-lb at 250 cycles per minute. (f) Because of excessive porosity and poor appearance, joints were not tested.

Fig. 31. Aircraft drive-shaft assembly for which submerged-arc welding was selected on the basis of weld quality and production rate (Example 223)



Automatic Submerged-Arc Welding

Joint type	T
Weld type	35° groove with ⅜-in. fillet-weld reinforcement
Welding position	Flat
Number of passes	One
Preheat and postheat	None
Electrode wire	3/16-in.-diam EH14
Flux	F71
Electrode stickout	1 in.
Power supply	1000-amp transformer
Current	700 to 750 amp, ac
Voltage	28 to 32 v
Travel speed	10 to 15 in. per minute

Fig. 32. Military-vehicle wheel that was redesigned for production as a weldment with a hardened wear surface, to save material, time, and the cost involved in previous use of a riveted wear ring (Example 224)

sectioned and examined to ensure that the welding was under control. In terms of labor costs, time and materials, the design and manufacturing operation for the welded wheels was less costly than the original design and production method.

Gas Tungsten-Arc Welding

In gas tungsten-arc welding, the composition of the weld metal can be accurately controlled, because in gas tungsten-arc welding any filler metal used is fed into the weld puddle and not into the arc (see the article on Gas Tungsten-Arc Welding, beginning on page 113 in this volume). Control of weld-metal composition is generally more important in the welding of alloy steel than in the welding of plain low-carbon steel; in most applications, composition control becomes more important as the alloy content of the base metal increases.

The close control of heat input that is a characteristic of gas tungsten-arc welding is frequently advantageous when welding alloy steel in the heat treated condition (see Example 201).

The main disadvantage of the gas tungsten-arc welding of alloy steel is the same as for other steels; the process is slower and consequently somewhat more expensive than the other metal-arc processes. However, for many critical applications the need for the high-quality welds that can be obtained by the gas tungsten-arc process does not permit substitution of another metal-arc process.

The four examples that follow describe details of practice for gas tungsten-arc welding of medium-carbon alloy steels (see also Example 201).

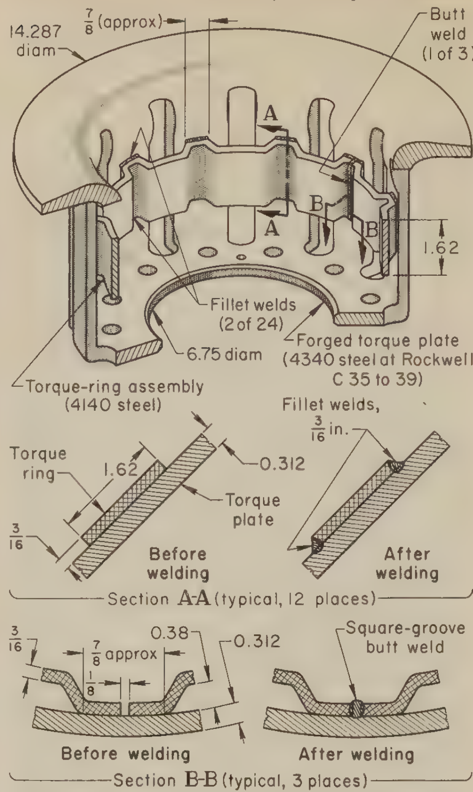
Example 225. Welding of 4140 Steel Stampings to a Heat Treated 4340 Forging (Fig. 33)

When undesirable vibrations were traced to the 4340 forged steel torque plates of an aircraft brake assembly, the design was revised to incorporate an integral ring of metal that changed the resonance frequency of the part. In order to make use of 1500 existing torque plates, they were altered by gas tungsten-arc welding a torque ring stamped from annealed 4140 steel to the inside of each heat treated 4340 steel torque plate as shown in Fig. 33. This weldment served the same purpose as the redesigned torque plate. As shown in Fig. 33, the torque ring, which was stamped in three segments, had a corrugated configuration to avoid interference with brake flange mounting bolts. The three segments of the ring were joined by square-groove butt welds, and the ring was attached to the torque plate with two fillet welds at each of the 12 corrugations (24 fillet welds), as shown in Fig. 33.

Although the welds were required only to hold the ring in solid contact with the torque plate, no cracking could be tolerated. In addition, the heat treated hardness of the 4340 steel torque plate (Rockwell C 35 to 39) had to be retained. Therefore, it was necessary to establish precise procedures for preheating, maintaining temperature during welding, and postheating.

Before welding, the parts were cleaned in an alkaline cleaning solution and rinsed. The ring segments were positioned and clamped in a locating jig and tack welded to the torque plate. The assembly was then furnace preheated to 400 F in an argon atmosphere. From this time until the welded assembly was ready for stress relieving, the temperature was not permitted to drop below 350 F, nor to rise above 500 F. Temperature-sensitive crayons were used. When

4140 steel welded to 4340 steel; Hastelloy W filler metal



Conditions for Gas Tungsten-Arc Welding	
Joint types	Butt and lap
Weld types	Square-groove and fillet
Number of passes	One
Preheat	400 F
Interpass temperature	350 to 500 F
Postheat	Maintained at 400 to 500 F until stress relieved at 980 to 1000 F for 3 hr; furnace cooled
Fixtures	Locating jig
Shielding gas	Argon
Filler metal	Hastelloy W (AMS 5786)

Fig. 33. Heat treated torque plate to which a three-piece torque-ring assembly was welded to eliminate vibrations (Example 225)

temperature dropped to 350 F, the weldment was heated with torches; when temperature rose to 500 F, welding was temporarily stopped.

Argon shielding and a Hastelloy W filler rod were used. Heat input was controlled solely by manipulating the arc; no remote current-control device was employed. To minimize residual shrinkage stress, the butt joints were welded last. Each weld was made in one pass, which was interrupted three or four times, depending on heat buildup. Welding conditions were the same for the fillet and butt welds.

After being welded, weldments were maintained at the welding temperature in an argon-atmosphere furnace until a furnace retort load was ready for stress relieving. Weldments were stress relieved at 980 to 1000 F for 3 hr and furnace cooled, after which the joints were sand blasted and inspected for cracks by visual and fluorescent liquid-penetrant examination. Following an alkaline cleaning cycle similar to preweld cleaning, the joints were shot peened, using an S-330 shot, to produce a surface compressive stress (150% coverage; 0.010 to 0.014-in. intensity). On the first ten pieces only, radiographs were taken to ensure that the weldments were acceptable.

Example 226. Use of Preliminary Buttering To Permit Welding of 4340 Steel Without Preheating (Fig. 34)

A conventional gas tungsten-arc welding process could not be used for joining two shell sections of a naval torpedo, because of difficulties in preheating. The shell sections, as shown at left in Fig. 34, were machined from normalized 4340 steel forgings, which required preheating at 500 to 700 F to prevent cracking after welding. However, the forward shell contained a shrink-fitted tank forged from aluminum alloy 5254, which could not be heated above 250 F without loss of strength. This restriction was overcome by a two-stage procedure that permitted the final closure to be made by gas tungsten-arc welding without the need for preheating. The procedure involved the use of a submerged-arc buttering deposit, as described below and illustrated in Fig. 34.

Both shells were received as oversize pierced forgings, requiring considerable machining. During initial machining, a large circumferential groove was cut in each shell in the location that subsequently would become the joint area (see top middle view in Fig. 34). These grooves were filled by submerged-arc welding, after a 700 F preheat, using a low-carbon steel electrode. Immediately after welding, the shells were given a stress-relieving treatment at 1250 F for 2 hr, and then were heat treated to a hardness of 311 to 375 Bhn.

Machining was resumed to obtain the configurations shown in the bottom middle view in Fig. 34. Next, the aluminum tank was shrink-fitted to the forward shell. The two shells were then aligned in a fixture to form the weld groove shown at upper right in Fig. 34. Finally, the assembly was mounted on a rotating positioner, and joined by automatic gas tungsten-arc welding with a low-carbon steel filler metal (Fig. 34, lower right). Because the buttering welds formed the base and sides of a continuous groove of low-carbon steel, the weld that joined the shells could be made without preheating and without the risk of cracking.

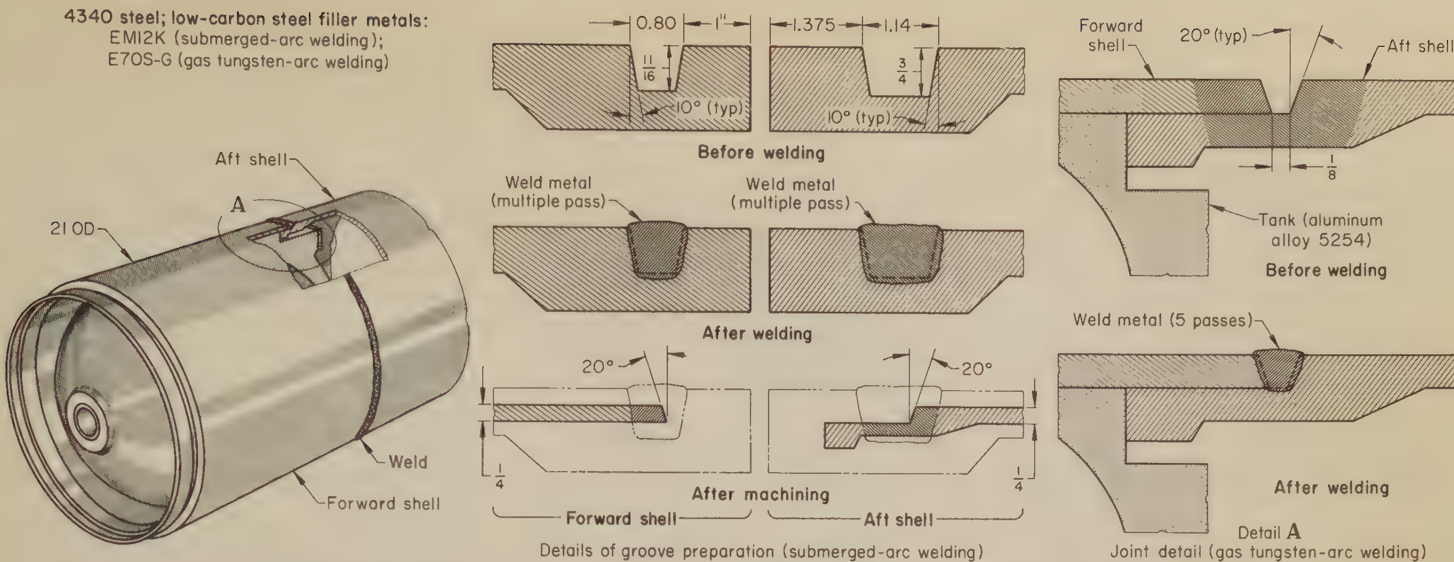
Both welding operations were carefully planned and executed, and the welds were thoroughly inspected. Submerged-arc welding was done with a $\frac{3}{32}$-in.-diam electrode and electrode-and-flux combinations having the AWS classifications EM12K-F71 and EM12K-F72.

Up to eight passes were required for buttering by submerged-arc welding. Interpass temperature was maintained within the range of 500 to 800 F. The first two passes were made using the EM12K-F71 combination at 300 amp, 27 to 28 volts, with straight polarity. Passes 3 to 8 were made using the EM12K-F72 combination at 420 amp, 28 to 29 volts, with reverse polarity. It was important to avoid excessive alloying of the filler metal with the base metal, which could have caused cracking. The change in flux type (same filler metal) for passes 3 to 8 was made to improve impact properties by reducing dilution of the weld metal. The joint areas (Fig. 34, middle views) were machined from low-dilution weld metal. These areas were required to meet stringent radiographic inspection. Slag was carefully removed after each pass. Weld starts, crossovers and any doubtful areas were ground to clean metal.

Gas tungsten-arc welding of the girth joint was done in five passes, using an automatically programed procedure. Details of welding conditions are given in the table with Fig. 34. Since both joint and filler metal were of low-carbon steel, preheating was not needed, but in order to prevent overheating the aluminum tank, it was necessary to limit interpass temperature to 200 F. Temperature at the joint was checked with temperature-indicating crayons. At the end of each pass, current automatically tapered off over a 10-sec trailing time, and the weld was wire brushed. After welding, the assembly was finish machined and ground to a 32-micro-in. finish.

Examples 227 and 228. Welding of High-Strength Alloy Steel Rocket-Motor Cases in the Annealed Condition

Example 227 (Fig. 35). Automatic gas tungsten-arc welding provided the precision and reliability required for joining the sec-



Automatic Gas Tungsten-Arc Welding

Joint type	Butt, with integral backing
Weld type	V-groove
Welding position	Flat
Fixtures	Clamping jig, rotating positioner
Number of passes	Five
Preheat and postheat	None
Interpass temperature	200 F max
Shielding gas	Argon, at 24 cfh
Torch	Machine type with gas lens
Electrode	3/32-in.-diam EWTh-2
Filler metal	1/16-in.-diam E70S-G
Welding speed, all passes	35 ipm
Power supply	300-amp, constant-current transformer-rectifier(a)
Current (dcsp) and voltage:	
Pass 1	260 amp, 11⅞ v
Pass 2	285 amp, 12 v
Pass 3	290 amp, 12¼ v
Pass 4	295 amp, 12⅜ v
Pass 5	300 amp, 12½ v

(a) With slope control and programer

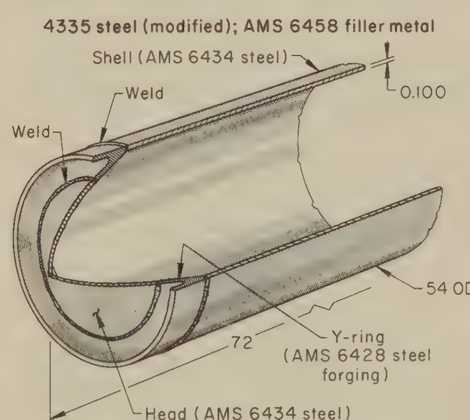
Fig. 34. Alloy steel forward and aft shells of a naval torpedo that were joined by gas tungsten-arc welding using no preheating (to avoid weakening of a pressed-in aluminum alloy tank), by first employing submerged-arc welding to make a buttering deposit of low-carbon steel filler metal in joint areas before machining (Example 226)

tions of a 54-in.-OD solid-propellant rocket-motor case. Figure 35 shows a section taken through the forward end of the 72-in.-long vessel (the aft end has been omitted). The branched section shown constituted the forged and machined Y-ring, made of AMS 6428 (4335 modified) alloy steel, which joined the cylindrical spun shell and the spherically dished forward head, both of AMS 6434 (4335 modified) alloy steel. The short stub of the Y-ring served for the later attachment of a supporting skirt. The Y-ring design provided optimum stress distribution for the welded joints and also afforded easy access to the joints for welding, radiographic inspection, and repair.

The motor case was designed to be welded in the annealed condition. After being welded, the vessel was heat treated to develop a minimum yield strength of 190,000 psi. At this strength level, a wall thickness of only 0.100 in. satisfied service requirements for strength and low weight. However, extremely reliable, defect-free welds were necessary. Weld design consisted of circumferential square-groove butt joints, with no root opening, welded from the outside only. There were no longitudinal seams. To obtain weld-metal properties matching those of the base metal, AMS 6458 was used for filler metal. This filler metal had been prepared by vacuum melting (composition is given in the table with Fig. 35).

Sections of the motor case were assembled on turning rolls, using internal and external clamping fixtures to ensure accurate alignment of the joint. Internal stainless steel backing that incorporated electrical resistance heaters for preheating and copper backing grooves for gas shielding was installed. Joints were welded in a single pass by rotating the assembly under a stationary welding head equipped with automatic wire feed and automatic voltage control. Additional welding conditions are given in the table with Fig. 35.

Example 228 (Fig. 36). The principal welded components of a typical D-6ac rocket-motor case, shown at upper left in Fig. 36, were a machined forward dome, two spun cylindrical sections, and a machined aft adapter (mechanically joined to an aft closure). Thus, the vessel design eliminated longitudinal joints, which would be subjected to hoop stresses, and required only three girth welds, which would be subjected to stresses of a lower order. To



Conditions for Automatic Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Square-groove (no root opening)
Welding position	Flat
Number of passes	One
Preheat	400 to 500 F
Postheat	900 F(a)
Fixtures	Rotating positioner, external and internal clamping rings, stainless steel backing
Shielding gas, at torch	Helium, at 100 cfh
Backing gas	Argon, at 35 cfh
Torch	Fixed
Electrode	⅛-in.-diam EWTh-2, taper ground
Filler metal	0.047-in.-diam AMS 6458(b)
Filler-metal feed rate	25 to 30 in. per minute
Current	95 to 125 amp, dcsp
Voltage	13 v (automatic control)
Travel speed	8 to 10 in. per minute

(a) Joint area only, by radiant heat. (b) 0.30 C, 0.71 Mn, 0.62 Si, 1.25 Cr, 0.50 Mo, 0.30 V.

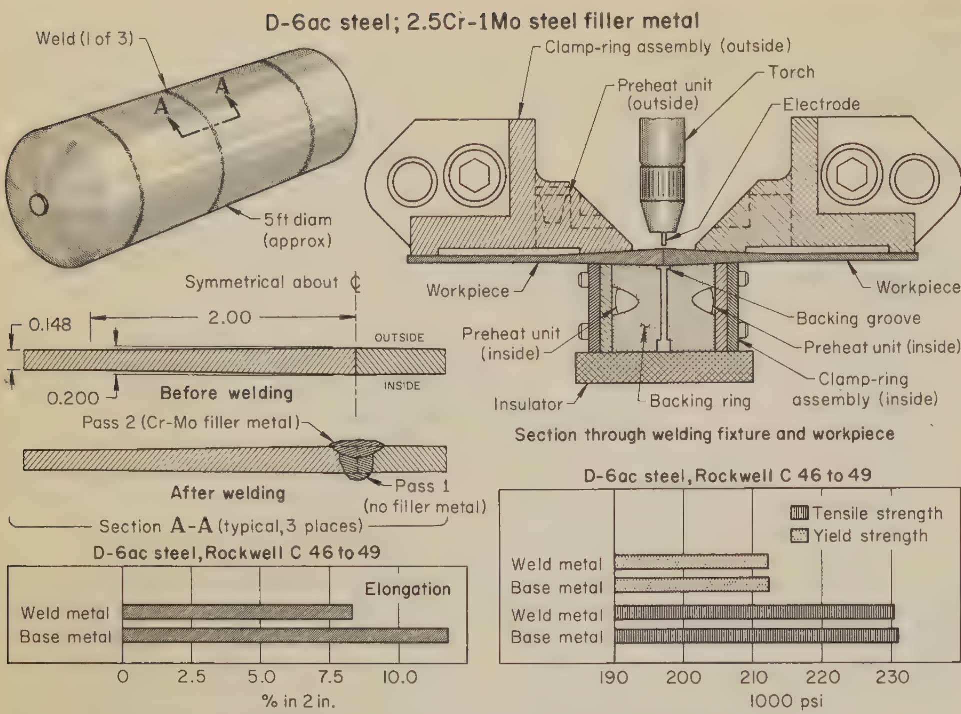
Fig. 35. Forward end of a rocket-motor case that was welded in the annealed condition. The forged Y-ring joined the drawn head and the shell. (Example 227)

reduce operating stresses in the welded joint further, the sheet thickness at the joint was increased approximately one-third, as shown in section A-A in Fig. 36. Mechanical properties of the welded joint closely comparable to those of the base metal were desired. The first step was to ensure cleanness of base metal and filler metal. Investigation established that using a 2.5Cr-1.0Mo steel filler metal resulted in the optimum combination of strength, fracture toughness, and resistance to cracking. A typical filler-metal composition was: 0.14 C, 0.54 Mn, 0.39 Si, 2.55 Cr, 1.02 Mo.

To obtain the desired joint strength properties repeatably and reliably, the gas tungsten-arc process was selected because of its capability for precise control. The gas-shielded arc and relatively low welding speed afforded good operator visibility for monitoring the operation. A voltage-controlled welding head, which facilitated precise control of arc length, was employed. The thickness at the joint (0.200 in.) made it possible to complete the joint in two welding passes, working from the outside of the vessel.

It was necessary to design a large, complex welding fixture, the functions and features of which were:

1 Two large end frames, at the headstock and tailstock, gripped the ends of the assembly by means of air-actuated toggle clamps and provided precise rotational speed through coordinated variable-speed drives.
2 Three two-piece round-out rings of box-shape cross section were bolted on the shell exterior to prevent the thin-wall vessel from bulging under its own weight. Each ring was supported by a set of freely rotating tank rolls.
3 An external clamp-ring assembly, bolted in place at either side of the joint, forced the joint edges into alignment against an internal, segmented backing ring expanded into position by an air-operated spider supported on a central mandrel. Figure 36 (upper right) shows the joint held between external and internal clamp rings with the electrode holder in position for welding. A continuous groove cut into the backing ring served to confine the underside of the weld and to supply gas shielding by means of a series of gas ports drilled through the backing. External shielding was supplied by the torch nozzle and by a short trailing



Conditions for Automatic Gas Tungsten-Arc Welding

Joint type	Circumferential butt	Electrode	⅛-in.-diam EWTh-2
Weld type	Square-groove (no root opening)	Torch	⅝-in.-diam cup, 500 amp, water cooled
Welding position	Flat	Filler metal:	
Number of passes	Two	Pass 1	None
Preheat	500 to 650 F	Pass 2	0.060-in.-diam Cr-Mo steel(a)
Postheat	1200 to 1250 F for 1 hr	Power supply	400-amp motor-generator
Shielding gas, at torch:		Current (both passes)	150 to 220 amp, dcsp
Pass 1	88% helium – 12% argon, at 40 cfh	Voltage (both passes)	9 to 11 v
Pass 2	Argon, at 35 cfh	Arc starting	High frequency
Trailing gas (both passes)	Argon, at 20 cfh	Travel speed (both passes)	4.5 in. per minute
Backing gas (both passes)	Argon, at 25 cfh		

(a) 0.14 C, 0.54 Mn, 0.39 Si, 2.55 Cr, 1.02 Mo.

Fig. 36. Rocket-motor case (upper left), *showing three girth welds;* (left center) *joints before and after welding;* (upper right) *sectional view of welding fixture and joint in workpiece, with torch in position for welding;* (bar charts) *tensile properties of base metal and weld metal after heat treatment* (Example 228)

shield that protected the newly formed weld from atmospheric contamination until it had cooled sufficiently to be unaffected.

As shown in Fig. 36, preheat units (resistance heaters) were embedded in the external clamps and the backing ring. These units were used to maintain a preheat temperature of 500 to 650 F during the welding operation. Not shown is the split wraparound induction coil that supplied a 1200 to 1250 F local postheat cycle immediately after welding. The coil was powered by a 50-kw, 400-Hz motor-generator.

4 The welding fixture incorporated an observation platform that straddled the workpiece and enabled the operator to monitor the operation. The platform, tank rolls, end frames, headstock and tailstock were driven on the ways of the fixture bed.

The welding equipment comprised a 400-amp, dc power supply, a wire-feed drive with flow control for gas and cooling water, a gas tungsten-arc voltage-controlled welding head, and an electronic programing unit that coordinated the initiation, duration and termination of all elements of the welding cycle. The power supply was additionally equipped with upslope and downslope control of welding current to provide easy starts and to avoid formation of terminal craters. A high-frequency generator was integrated into the welding circuit to aid arc initiation. The above equipment, apart from the power supply and the high-frequency generator, was mounted on the boom of a manipulator within easy reach of the operator on the observation platform.

After the square-groove butt joint had been machined, the joint edges were polished bright with an 80-grit abrasive drum sander and cleaned by wiping with acetone. Roundup rings were then bolted on the forward dome and the first shell section. The forward dome was inserted in the end frame, the internal backing adjusted, and the external clamp ring attached. The first shell section was then loaded in position and clamped. Maximum allowable mismatch at joints was 0.020 in.

Welding was started when the joint attained preheat temperature, and the two passes were made without stopping. Pass 1 was made without filler metal. For the start of pass 2, the operator initiated wire feed by pushbutton. Welding was done in the flat position with the torch fixed at the top, or 12 o'clock position. The pass was terminated with downslope control.

After being welded, the joint was induction heated at 1200 to 1250 F for 1 hr. After cooling, both surfaces of the weld were ground smooth with abrasive belts of grit sizes 50 through 150, to facilitate inspection by radiographic and magnetic-particle methods.

The sequence was repeated for each of the two other joints. When completed, the entire vessel was heat treated to a hardness of Rockwell C 46 to 49. Further details of welding conditions are given in the table with Fig. 36.

Tensile properties of weld metal and base metal after heat treatment are shown in the graphs in Fig. 36. As the graph at the right shows, weld-joint yield strengths were in excess of 210,000 psi. In addition, the joints consistently withstood hydrostatic proof testing at 90% design pressure. Proof tests established the integrity of the entire vessel under stresses equivalent to those expected in service.

Plasma-Arc Welding

Plasma-arc welding is generally considered as a refinement of gas tungsten-arc welding. It offers the close control of composition and heat input that are obtainable with gas tungsten-arc welding, but is much faster. Thus, the process is sometimes used for welding alloy steel when quality requirements are stringent and production quantity is moderate or high.

Disadvantages of the plasma-arc process for welding alloy steel are the same as for welding other metals — namely, high initial cost of equipment and high maintenance cost (see the article on Plasma-Arc Welding, beginning on page 138 in this volume).

Codes, Standards and Regulations

Boilers and Pressure Vessels. Codes, standards and regulations applicable to the construction and maintenance of welded boilers and pressure vessels include:

1 ASME Boiler and Pressure Vessel Code, Sections I to X, and Case Interpretations
2 U. S. Navy: MIL-STD-248, 271, and 278; NAVSHIPS 250-1500-1
3 Marine Engineering Regulations and Materials Specifications; U. S. Coast Guard
4 American Bureau of Shipping Rules for Building and Classing Steel Vessels
5 Standards; Tubular Exchanger Manufacturers' Association, Inc.
6 Lloyd's Rules and Regulations; Lloyd's Register of Shipping
7 CSA Standard B51-1965, Code for Construction of Boilers and Pressure Vessels; Canadian Standards Association.

Bridges and Similar Structures. The following specifications apply to bridges and similar welded structures that are subjected to frequent variations in loading intensity:

1 Specifications for welded highway and railroad bridges: AWS D2.0-66
2 Specifications of the American Association of State Highway Officials
3 Specifications of the American Railway Engineering Association.

Buildings. Specifications for welding in building construction are covered by AWS D1.0-66. These specifications are in general agreement with the AISC Specification for Design, Fabrication and Erection of Structural Steel for Buildings.

Field-welded storage tanks are usually constructed in accordance with codes prepared to meet the needs of a specific industry only. Tanks for water are covered by: Standard for Steel Tanks, Standpipes, Reservoirs and Elevated Tanks for Water Storage (AWWA D100-65; AWS D5.2-65). Welded tanks for oil storage are covered by API Standard 650 (Dec 1961).

Industrial piping is covered by several codes and standards, including:

1 ANSI Standard B31, Code for Pressure Piping, Sections 1 through 8
2 ASME Boiler and Pressure Vessel Code, Sections I, III, VIII and IX
3 API Standard 1104
4 AWWA standards covering fabricated piping
5 Pipe Fabrication Institute standards
6 U. S. Navy Bureau of Ships Specifications NAVSHIPS 250-582 and 250-1500-1
7 Procedures by The Heating, Piping and Air Conditioning Contractors National Association.

Nuclear-power pressure vessels are covered by ASME Boiler and Pressure Vessel Code, including Section III and Case Interpretations; also by ANSI Standard B31, Code for Pressure Vessel Piping (together with its Case Interpretations).

Railroad Tank Cars. The Interstate Commerce Commission and the Association of American Railroads regulate the design, specifications and codes for manufacture of tank-car frames and vessels.

Transmission pipelines are covered by API Standard 1104, Field Welding of Pipelines; also by ANSI Code for Pressure Piping — Oil and Gas Piping Systems.

Arc Welding of Cast Irons

*By the ASM Committee on Welding of Cast Irons **

SATISFACTORY JOINTS have been obtained in gray, ductile and malleable cast irons by arc welding. The tensile strength of welded cast iron joints is usually less than that of the base metal, and the heat-affected zone is usually harder and more brittle than the original casting. Lack of reproducibility in joint tensile strength has also been observed. Nevertheless, large quantities of iron castings are welded successfully by the processes discussed in this article.

Most welding is done on gray iron and the least on malleable iron. The welding of ductile iron occupies an intermediate position.

The three major areas of application of welding to cast iron are:

1 Repair of casting defects in the foundry
2 Repair of castings that have become damaged or worn in service
3 Production of welded assemblies.

Repair of Casting Defects. Repair welding of defects in new iron castings represents the largest single area of application of welding to cast iron. Minor defects, such as porosity, sand holes, washouts, cold shuts, or shift, can usually be repaired. Thousands of tons of new automotive engine blocks are repaired annually by arc and oxyacetylene welding. Braze welding is also used in applications where the color contrast of the copper-base filler metal is not objectionable. Repair welding of defective castings is described in Examples 229, 230 and 234.

Casting defects discovered during machining, or resulting from machining errors, are also repaired by welding. Repairing of machined castings is often done by shielded metal-arc welding using nickel-iron electrodes (ENiFe-CI). This filler metal provides welds that are less brittle than those made with cast iron electrodes (ECI), and a better color match than can be obtained with braze welding.

Arc welding is faster than oxyacetylene welding, and causes less distortion. Although the welding temperature is high in arc welding, the total heat input is lower than for oxyacetylene welding, because of the high speed and the small area heated in arc welding. Thus, the heat-affected zone is less for arc welding than for gas welding.

Repair of Damaged Castings. Castings that have cracked or broken in service can often be repaired by arc welding. Worn surfaces of castings can also be rebuilt. Filler metals are available for building up worn parts to obtain bearing surfaces or resistance to abrasion and corrosion.

In repairing damaged castings, the conditions under which the welding must be done may be unsuitable for good welding practice, and they may call for extra care and improvisation, sometimes under the pressure of an emergency. Castings that have been in service for a long time may need special attention to the removal of oil and other foreign matter that has impregnated the casting by way of graphite flakes or microcracks. Edge preparation may involve veeing out a crack. These operations must be thorough if the repair is to stand up in service. If furnace heating is impractical, improvised methods of preheating and postheating may be required. For example, a furnace may have to be constructed around the part, or local preheating may be required, depending on the size, shape and intended use of the part.

If the cost can be borne, shielded metal-arc welding, using nickel-iron electrode ENiFe-CI, is preferred. Generally, however, the repair of broken castings is done under whatever conditions and with whatever electrode the circumstances demand or will permit.

Production of assemblies by welding iron castings to other iron castings or to other metals offers several advantages. An increasing number of ductile and malleable iron castings are joined in this manner, and some gray iron castings as well. Assemblies produced by welding are described in Examples 232 and 233 (gray iron), Examples 235 and 236 (ductile iron), and Examples 238 to 241 (malleable iron).

For speed, an arc welding process is usually preferred, but oxyacetylene braze welding and oxyacetylene welding (see the articles that begin on pages 579 and 583) are also used.

Weldability

Cast iron is considerably less weldable than low-carbon steel. Cast iron contains much more carbon and silicon than does steel, with the result that cast iron is less ductile, and, when welded, is subject to more metallurgical complications in both the weld metal and the heat-affected zone.

Weld-Metal Area. In addition to the normally expected constituents (graphitic carbon, pearlite and ferrite), the microstructure of a gray iron weld deposit may contain massive (free) carbide and martensite. The presence of these constituents, and their size, form and distribution, are the combined effects of: (*a*) the carbon and silicon contents of the weld deposit and (*b*) the cooling rate in the weld area.

If a weld is made, with a cast iron electrode, in a malleable iron or a ductile iron casting, the carbon is mostly in the combined form. The graphite that precipitates from the molten weld metal during cooling is in flake form, as in a gray iron casting, and not in spheroidal form, as in a malleable iron or ductile iron casting. The flake graphite reduces the ductility of the area in which it occurs. For these reasons, welds having the ductility of the base metal usually cannot be made with cast iron electrodes.

Heat-Affected Zone. The temperature produced in the heat-affected zone is usually high enough to transform the base metal to austenite, provided carbon is available. When rapidly cooled, high-carbon austenite transforms to brittle martensite.

The ferritic grades of gray and ductile iron do not readily form austenite on heating (and martensite on cooling) because nearly all of the carbon is in the form of graphite and the time at temperatures above the transformation range is too short for diffusion of carbon from the graphite.

The pearlitic grades of gray and ductile iron readily form martensite when rapidly cooled from above the transformation range, because the combined carbon content of the pearlitic matrix is rapidly dissolved to form high-carbon austenite when heated.

Martensite. The martensite formed in the weld deposit and in the heat-affected zone behaves in the same way as the martensite in a quenched steel; it can be transformed into softer products by tempering. The heat for tempering can be supplied by preheating and welding, followed by protected cooling, or by preheating, welding and postheating, or (less commonly) by welding and postheating.

The heat of welding alone in single-pass arc welding will not temper the martensite enough to provide reasonable machinability or to reduce the danger of postweld cracking to an acceptable level. In multiple-pass welding, each succeeding bead tempers the one underneath or adjacent to it. Additional tempering is provided by the cumulative heating effect of the passes.

The alternative to tempering the martensite is to modify the welding procedure by reducing the heat input to produce a narrower heat-affected zone and thus to decrease the amount of martensite formed.

Free Carbides. Once free carbides are formed in the weld or the heat-affected zone, the only way they can be broken down into softer constituents is by an-

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Several examples in this article were contributed by members of other Metals Handbook welding committees.

Table 1. AWS Classifications and Nominal Compositions of Filler Metals Commonly Used for Arc Welding Cast Iron (Adapted From AWS A5.15-69)

Classification	Composition, % C	Si	Mn	Fe	Ni	Cu	Other
Nickel-Base Filler Metals							
ENi-CI	2.00	4.00	1.00	8.00	85.0 min	2.50	...
ENiFe-CI	2.00	4.00	1.00	Rem	45.0-60.0	2.50	...
ENiCu-A	0.35-0.55	0.75	2.25	3.0-6.0	50.0-60.0	35.0-45.0	...
ENiCu-B	0.35-0.55	0.75	2.25	3.0-6.0	60.0-70.0	25.0-35.0	...
Cast Iron Filler Metal							
ECI	3.25-3.50	2.75-3.00	0.60-0.75	Rem	Trace	...	...
Low-Carbon Steel Filler Metal							
ESt	0.15	0.03	0.30-0.60	Rem	...	...	...
Copper-Base Filler Metals							
ECuSn-A	...	...	...	...	...	Rem	4.0 to 6.0 Sn
ECuSn-C	...	...	...	...	...	Rem	7.0-9.0 Sn
ECuAl-A2	...	0.10	...	1.5	...	Rem	9.0-11.0 Al

nealing at 1600 F or higher. Such treatment may be undesirable because it increases the cost of the weldment and may reduce the tensile strength of the base metal.

The alternative is to prevent, whenever possible, the formation of carbides or, failing that, to reduce their occurrence to manageable proportions. Several methods for preventing or reducing carbide formation can be employed, either singly or in combination.

First is the use of a cast iron electrode (Table 1) of a composition that will produce, after deposition losses of silicon, carbon and manganese, a solidified weld metal of approximately the same composition as the base metal. This eliminates dilution of the weld metal, a first step in reducing the formation of free carbides.

The second method is to preheat the casting to the maximum temperature that is consistent with the acceptable losses in casting hardness and strength. In practice, this temperature seldom exceeds 1200 F for general preheating. Increasing the time for dissipation of heat delays the cooling of the weld area to enable the previously formed free carbides to break down.

When properly applied, a combination of these two methods will, for all practical purposes, reduce the carbide problem in gray or ductile iron.

A third method is to use one of the high-nickel or nickel-copper filler metals (Table 1). Because both nickel and copper are effective graphitizers and do not form carbides in cast iron, their presence in the weld effectively reduces carbide formation.

A fourth method is to reduce the heat input. In gas metal-arc welding, the short-circuiting arc is often used because it can be accurately controlled to the point where only enough base metal is melted to effect a bond with the filler metal. This reduces the amount of base metal available for formation of free carbide during subsequent solidification. When a nickel or nickel-copper electrode is used with a short-circuiting arc, the formation of free carbide is inhibited to the extent that the weld is usually machinable, although at a reduced rate.

Graphite. Once graphite forms in the weld deposit, it will precipitate as flakes. This behavior creates a problem in the welding of malleable and ductile irons.

Malleable iron weldments can be given a full malleablizing treatment. Although this treatment will be reasonably successful if the composition of the weld deposit is about the same as that of the base metal, it is economically unattractive. If a steel filler metal is used, hard phases will form in that portion of the deposit in which there is dilution by the base metal.

Flake graphite in the weld deposit in ductile iron cannot be converted to the nodular form.

Stresses. The weld area will be under shrinkage stress. Cracks may occur on or beneath the surface of the weld deposit, in the heat-affected zone, or in the base metal, depending on the stress intensity and distribution. The methods employed to control or to prevent the formation of free carbide and to reduce the formation of martensite, or to transform it to softer products, also act to reduce the stress level in the weld and adjacent areas. The degree of effectiveness of these measures depends on the maximum temperature attained and the cooling rate.

Welding Procedures

An important step in many procedures for welding cast iron is the designation of those areas on a casting where welding is permitted, including restrictions as to the type of weld allowed. Such designations, or their converse — areas where welding is *not* permitted — may be in the form of marked drawings, specially prepared sketches, or marked photographs of castings.

As a rule, welding of any kind is prohibited in highly stressed areas or in areas where the failure of a weld would result in failure of the casting. Welds on surfaces to be machined are acceptable, provided the area is not highly stressed.

Repair welding is used extensively on cast engine cylinder blocks and heads, but it is generally prohibited on the fire deck, water jacket, main bearing supports and their supporting ribs, cylinder-head stud bosses, and cylinder bores. Repair of defects on pan rails, bell-housing flanges, and valve-cover flanges, and buildup of short-run attachment pads and bosses for hold-down stud holes in heads, are often allowed. There are no fixed rules; each user sets his own requirements. Some prohibit the welding of any porous area or crack or any defect that penetrates the casting wall; others permit such repair, provided a hole is drilled at each end of the crack and a complete-penetration weld is made. One user permits welding in the unjacketed part of a cylinder bore.

Preparation for any weld repairs, except faulty bosses and pads and similar surface defects, is a relatively simple procedure that involves:

1. Removing enough material to eliminate the defect completely
2. Producing a weld area of such configuration that there is room to manipulate the electrode or electrode holder.

When the defect requires V-shape preparation, an included angle of 60° is usually sufficient. The smaller the included angle, consistent with accessibility, the shorter the welding time, because less filler metal is required. When the defect penetrates the section, a suitable land should be provided whenever possible. In thin sections, a backing may be needed; in thicker sections (1 in. or more), preparation of the joint by double-V grooving is desirable.

Preheating

The presence of a brittle zone at the weld, caused by rapid freezing of weld metal and rapid cooling of weld metal and adjacent base metal, reduces the ability of the joint to withstand tensile stress in service and makes the joint susceptible to cracking immediately after welding, as a result of local contraction stress. By heating the casting before welding, both of these adverse effects can be reduced. Preheating slows the rate of cooling in the critically heated zone, which induces the formation of a more favorable structure. Preheating also enables the entire casting, or a large part of it, to contract with the weld zone, thereby minimizing the development of residual stress in metal near the weld area. Metal in the weld area can also benefit from preheating, because the weld metal cools more slowly through the transformation range and therefore develops softer microstructures.

High preheats produce softer, less brittle microstructures than do low preheats. With high preheats, however, welding is more difficult. The casting must be insulated from rapid loss of heat so that the preheat temperature can be maintained throughout the welding operation. The heat input from welding can be used to help maintain interpass temperature in small and medium-size castings. In large castings, steep thermal gradients should be avoided to prevent cracking.

To ensure proper control, temperature should be measured by contact pyrometers or temperature-indicating crayons at or near the weld zone and at as many other places as the casting size and heating method may indicate.

During welding of large preheated castings, the welder must be protected from the heat. This is usually done by exposing only the area being welded at the time, and by changing welders if the operation is of long duration. Preheat temperature must be maintained uninterruptedly until welding is completed. Recommended preheat temperatures are discussed in the individual sections of this article devoted to gray, ductile and malleable irons.

When repairing castings cracked or broken in service, cost is often of less concern than obtaining a satisfactory repair. In production welding, however, both time and cost are important. The manufacturer of the weldment cannot afford to lose the advantage of the low cost of iron castings by using costly welding procedures. For production welded assemblies, preheat costs are low when the castings are small and rapid welding procedures of low heat input are used. Joints are preferably located away from areas of high stress and surfaces to be machined. Since fast welding at low heat input produces a small heat-affected zone, preheat requirements are low. Under optimum conditions, arc welded joints have been made between ductile or malleable iron castings and low-carbon steel without preheat or postweld heat treatment. For most applications, however, preheating and postheating are advisable, either to reduce joint brittleness and residual stress or to improve machinability, or both.

Postweld Heat Treatment

Postweld heat treatment may consist of either full annealing or stress relieving. When heat treatment is not applied, the welded casting is usually cooled slowly from the welding temperature to room temperature by covering it with insulating material such as lime, ground asbestos, or vermiculite.

Stress relieving at 1150 F and then furnace cooling to at least 700 F is recommended whenever feasible.

Full annealing at 1650 F is sometimes employed to produce greatest softening of the weld zone or a more complete stress relief. However, annealing lowers the as-cast tensile strength of all but the softest irons.

In critical applications that require radiographic or ultrasonic inspection after heat treatment, castings often are inspected before treatment also, to save unnecessary costs if an internal defect should be present.

Preparation of Castings

Edge preparation is similar for all cast irons. Castings that have been in service are likely to be impregnated with oil or grease, and accordingly surface contamination should be removed with solvents, commercial cleaners, or paint removers, as required. Casting skin should be removed from surfaces to be welded and from adjacent areas by grinding, chipping, shot blasting, rotary filing, or equivalent means.

Blind cracks and pits must be completely dressed out to sound metal; otherwise, the heat of welding or subsequent service may propagate the defect. For this purpose, chipping, grinding, rotary filing, and machining are preferred to arc or gas cutting, which may propagate the defect through differential expansion. Magnetic-particle inspection is recommended to ensure that the crack has been completely removed. Some castings contain sealed internal passages that must be vented to prevent explosion during preheating.

Completely broken sections are dressed by any suitable method to form a single-V groove, leaving a $\frac{1}{16}$ to $\frac{1}{8}$-in. root face to align the parts. For arc welding, a 60° included angle (30° bevel) is usually adequate, although for thick sections a U-groove with a smaller groove angle may be used.

Heavy sections can be prepared for arc welding by using a double-V groove — that is, a V cut from both sides of the joint with a root face at or near the center to permit alignment.

Cleaning. Impregnated oil or other volatile matter can be eliminated by heating the casting or weld groove to approximately 900 F (dull red heat) for about 15 min and then wire brushing, grinding or rotary filing to remove the residue. This method has the advantage of degassing the casting and removing some of the surface graphite as well. Impregnated oil, gas and possibly carbon are major causes of excessive porosity in cast iron welds.

New castings present less of a cleaning problem than castings returned from service. However, casting skin, sand, and other foreign matter must be removed from the joint to be welded and the adjacent surfaces of the casting. Weld grooves are prepared as described above, according to the size of the defect or the desired joint. Castings that are gassy can be heated as described for impregnated castings.

Filler Metals

Cast iron, low-carbon steel, nickel-base alloys and copper-base alloys are the filler metals used in arc welding of cast iron. The covered electrodes classified in AWS-A5.15-69 for shielded metal-arc welding of cast iron are discussed below, where their principal features are summarized; nominal compositions are given in Table 1. In addition to those shown, the covered low-carbon steel, low-hydrogen electrode E7018 has been used (see Examples 233, 236 and 238). Where processes such as gas metal-arc welding are applicable, bare wire electrodes of low-carbon steel and nickel-base alloys also are used.

Covered nickel-base electrodes are classified as "pure" nickel (ENi-CI), nickel-iron (ENiFe-CI, 55% nickel), and nickel-copper (ENiCu). They are relatively expensive. The nickel and nickel-iron electrodes are widely used and the most successful.

Welds made with nickel electrodes are relatively ductile even when applied on thin sections without preheat, and are, therefore, easily machinable. Nickel welds are susceptible to cracking from phosphorus when the latter is present in the high quantities that are often present in gray iron. Because the phosphorus contents of ductile and malleable irons are lower than that of gray iron, nickel electrodes are well suited to these irons.

Nickel-iron electrodes are less expensive than the nickel type and are less susceptible to phosphorus-induced cracking.

The hardness of deposits from both nickel and nickel-iron electrodes will depend on dilution and cooling rate. Melting of the base metal should, therefore, be held to the minimum necessary. Preheating at temperatures of 300 to 600 F will aid machinability and help to reduce thermal stress. Peening with moderate blows, using a round-nose tool, can also be employed to reduce thermal stress.

Cast Iron Electrodes (ECI). Shielded metal-arc welding with cast iron electrodes must be on preheated parts, because of the high heat input of the arc. The method is fast for correcting small flaws, but because a high-temperature preheat is required, it offers no advantage over gas welding.

Steel electrodes (ESt) contain low-carbon steel cores with specially designed coverings to permit use at low amperage. Since the deposit is steel, it picks up carbon and produces a hard constituent in the fusion zone, unless it is used with a high preheat or the resulting weld is annealed.

Copper-base electrodes are of the copper-tin (ECuSn) or the copper-aluminum (ECuAl-A2) type. Arc welding with these electrodes can be considered a form of braze welding, since the filler metal melts at a much lower temperature than the iron. Heat input is higher than in gas or braze welding, although high deposition rates at low amperage are obtained. Deposits do not harden from carbon pickup, can absorb shrinkage stresses, and are machinable. Color match is poor. Wide grooves and thoroughly cleaned joints are essential for maximum bond strength. Preheats of 300 to 400 F should be used; slow cooling is necessary to benefit the heat-affected zone.

Differences in coefficient of expansion between filler metal and base metal are sometimes blamed when rupture tests show parting at the bond line, but if the weld is properly made, satisfactory strength can be obtained.

Copper-aluminum welds have higher strength than copper-tin welds and are used with higher-strength irons. These electrodes are also used in surfacing applications for bearings and for producing surfaces that resist corrosion and wear.

Various techniques can be used with these filler metals to improve joint quality. The following practices have been found to be helpful:

1. Use stringer beads.
2. Use low amperage.
3. When no preheat is used, the interpass temperature should not exceed 200 F. (Interpass temperature is the lowest temperature attained by the deposited weld metal before the next pass is started.)
4. When preheat is used, the interpass temperature should not exceed the preheat temperature.
5. To minimize welding stress, use a backstep sequence, with stringer beads no more than 2 to 3 in. in length. (In the backstep method, the weld is started about 2 to 3 in. from the normal starting point and welded back the same distance; subsequent beads are started and deposited similarly.
6. Avoid melting more of the cast iron than is necessary for fusion.
7. Whenever possible, deposit two or more layers, for best machinability.
8. Always strike the arc in the weld groove, never on the casting.

Gray Iron

High-carbon, high-silicon (ASTM class 20) gray irons are ferritic in structure, with coarse graphite flakes throughout the matrix. Low-carbon, low-silicon irons such as class 50 irons are pearlitic. The intermediate grades are mixed in structure, partly ferritic and partly pearlitic. (For detailed information on the relations among composition, section thickness, structure, and mechanical properties of gray iron, see the article on pages 349 to 365 in Volume 1 of this Handbook.) Ferritic gray irons are readily welded, but the irons of complex structure are, like high-carbon steel, difficult to weld.

When welded with no preheat, gray iron is heated quickly above the upper transformation temperature, absorbs carbon and is immediately chilled by the surrounding cold metal to temperatures at which martensite forms. Hence,

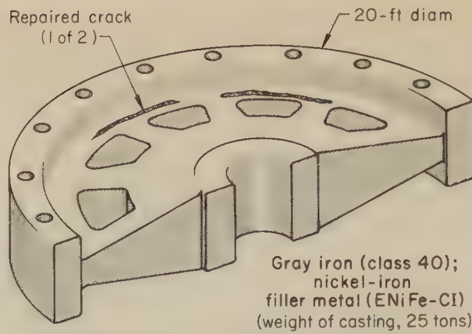
adjacent to the weld, there is a heat-affected zone that is hard and brittle. The weld, which consists of a mixture of base metal and filler metal, may be softer, but this depends largely on the composition of the filler metal used. If the iron is preheated, the heat-affected zone subsequently cools more slowly and transforms to softer products, rather than to hard, brittle martensite. The effect of preheating on the hardness of welds made by the shielded metal-arc process using nickel-iron electrodes is shown in Table 2.

Gray iron that has been welded with no preheat is difficult to machine. Cracking can also occur, since the metal shrinks in cooling and puts a tensile stress across the joint. If cooled slowly, the weld and the heat-affected zone are more likely to accommodate the stress before becoming cold. Similarly, stress relieving the weld areas at 1150 F while the weld areas are still hot will equalize stresses and help to prevent cracking.

Process Comparisons. Table 3 compares the processes most frequently used for welding gray iron and shows the color match and tensile strength ordinarily expected with good welding practice. Table 4 indicates the hardening effect of arc welding and of gas welding.

Gas metal-arc and gas tungsten-arc welding are expensive, chiefly because of the cost of the shielding gas used. Gas welding with cast iron filler metal gives the best color match, but it requires a high preheat — preferably at 1100 F or above — and a flux is required, to absorb the iron silicate slag. Generally, the choice of method is between shielded metal-arc welding with nickel or nickel-iron electrodes and gas welding with cast iron filler metal.

Shielded metal-arc welding with covered ("stick") electrodes is used on gray iron and ductile iron, and to a small extent on malleable iron. The type of deposit, and to some extent the procedure for welding, will vary according to the electrode used. Electrodes for manual welding of cast iron by the shielded metal-arc process are discussed in the foregoing section on Filler Metals.



Welding Conditions

Process ....Shielded metal-arc welding
Electrode ....3/16-in. ENiFe-CI(a)
Current ....160 amp, dcrp
Voltage ....24 v
Preheat (local) ....400 to 450 F
Postheat ....Cooled slowly to room temperature, then stress relieved at 1100 F(b)

Hardness After Stress Relief

Base metal ....178 to 187 Bhn
Weld metal ....169 to 176 Bhn
Heat-affected zone ....210 to 241 Bhn

(a) Covered electrode with 55% nickel – 45% iron. (b) Weld area was packed in asbestos; furnace was not immediately available.

Fig. 1. Large gray iron casting in which cracks were repaired by shielded metal-arc welding (Example 230)

Table 5 shows current ranges for four sizes of nickel-iron and nickel electrodes used in shielded metal-arc welding, and Table 6 shows ranges of welding current for three sizes of cast iron electrodes.

When using nickel electrodes (ENi-CI), the groove is prepared (see the section on Preparation of Castings in this article) and then the weld area or the entire casting is preheated to a temperature between 400 and 600 F. The weld is built up in successive passes not more than 1/8 in. thick, until the groove is completely filled. The casting can be cooled slowly under insulation, or can be stress relieved at 1100 to 1200 F and cooled slowly in the furnace.

Table 2. Effect of Preheat on Hardness of Shielded Metal-Arc Welds in Class 20 Gray Iron Welded With 3/16-In. Nickel-Iron (ENiFe-CI) Electrodes

Preheat temperature, F	Brinell hardness: Weld	Heat-affected zone	Base metal
No preheat	342-362	426-480	165-169
225	297-362	404-426	165-169
450	305-340	362-404	169
600	185-228	255-322	169-176

Table 3. Approximate Tensile Strength and Color Match Obtainable in Welded Joints in Gray Iron Using Different Processes(a)

Process	Filler metal	Base-metal class	Tensile strength of joint, psi(b)	Color match
Gas welding	RCI	30	25,000 to 30,000	Good
	RCI	40	30,000	Good
	RCI-A	40	30,000	Good
Shielded metal-arc welding	ENi-CI	30	25,000 to 30,000	Fair
	ENiFe-CI	30	25,000 to 30,000	Fair
	ENiFe-CI	40	36,000	Fair
	ESt	30	30,000	Poor to fair
	ESt	40	40,000	Poor to fair
Braze welding	RCuZn-A	30	(c)	Poor
	RCuZn-B	30	(c)	Poor
	RCuZn-C	40	(c)	Poor
	RCuZn-D	40	(c)	Fair
Gas metal-arc welding	Ni or Ni-Fe wire(d)	30	40,000	Fair
	Ni or Ni-Fe wire(d)	40	40,000	Fair
Gas tungsten-arc welding	Ni or Ni-Fe wire(d)	30	40,000	Fair
	Ni or Ni-Fe wire(d)	40	40,000	Fair

(a) Based on results reported from various tests and on production experience. (b) Approximate strength expected if good welding procedures and skilled operators are used. Wide variations in strength may occur as a result of variation in welding practice or in base-metal condition or size. (c) Joint strength approaching or equal to base-metal strength has been obtained, but large variations in strength have been observed because of variations in base-metal conditions or welder skill. (d) These filler metals are not classified, but wire coils and rods of compositions equivalent to ENi-CI and ENiFe-CI are obtainable.

Gas metal-arc welding is less well suited to welding gray iron than to welding ductile and malleable irons (see the discussion of gas metal-arc welding in the section on Malleable Iron, page 242). However, this process was used in welding a gray iron sump base to a steel plate in Example 233, which gives the welding conditions used.

Gas tungsten-arc welding can be used for joining gray iron. Joint preparation is the same as for shielded metal-arc welding, but a higher preheat is recommended. Argon or argon with an oxygen additive is used as the shielding gas. Welds have been made using nickel, nickel-iron, gray iron, and series 300 stainless steel filler metals, with straight-polarity direct current. Results are comparable to, but no better than, those obtained by other welding processes. Because no particular advantage is gained, gas tungsten-arc welding is not used when another, less costly process is available.

Examples of Practice. More welding of gray iron is done in the foundry repair of defects in new castings than in any other type of application. The arc welding process most frequently used is shielded metal-arc welding. The five examples of commercial practice that follow show how gray iron was welded in the repair of defects in new castings, in the salvage of worn or broken castings, and in the production of welded assemblies.

The repair of several defects in a pump casting intended for use in a paper mill is described in the first example that follows. Because the defects were discovered after final machining had been completed, scrapping the casting at this stage of production would have been expensive.

Example 229. Use of Shielded Metal-Arc Welding To Repair Casting Defects

During hydrostatic testing, two casting defects were detected in the machined gray iron housing of a large multiple-impeller pump. The defects were chipped out with an air gun, exposing two small voids that extended through unmachined sections of the housing wall, approximately 1½ in. thick. Further inspection showed a third defect, which was completely removed by chipping to a depth of ¾ in. Because the housing was fully machined, scrapping it would have been costly, and it was decided to repair the defects by welding.

The problem was to avoid distortion of the machined surfaces during welding and to deposit leakproof welds capable of withstanding a 150-psi hydrostatic test. Tapered weld grooves were chipped out, the largest measuring about 4 in. long and 1 in. wide at the surface. All traces of cutting oil were removed by solvent cleaning. To minimize heat input, shielded metal-arc welding, without preheat, was selected in preference to gas welding. A 1/8-in. ENi-CI electrode (85% nickel, min) was used.

To avoid overheating, beads not more than 1 in. long were deposited along the length of the weld groove, and the welding was alternated on the two sides; current was set at 90 amp, 22 volts, dcrp. Weld grooves were allowed to cool to 200 F (measured by temperature-indicating crayons) between successive passes. All beads

except the finish bead were peened. After welding, the casting passed the hydrostatic test. No distortion of the repaired and machined surfaces was detected.

The following example describes the repair welding of one half of a large gray iron retaining plate.

Example 230. Repair Welding of Cracks in a 25-Ton Casting (Fig. 1)

Shielded metal-arc welding was selected for repairing two cracks in the new 25-ton, 20-ft-diam gray iron casting shown in Fig. 1, because it was simpler, faster and less expensive than gas welding. Gas welding would have entailed high preheat in a large furnace, difficult welding conditions, and care in maintaining high interpass temperature. Shielded metal-arc welding, using a nickel-iron electrode (ENiFe-CI), was done with local preheat at 400 to 450 F.

Both cracks were dressed out to form 60° V-grooves by chipping and grinding. Crack depth varied from 1 to 1¾ in.; length was about 30 in. Magnetic-particle and dye-penetrant inspection methods were used to determine completeness of crack removal. The casting was then locally preheated, using gas torches; preheat temperature was checked by temperature-indicating crayons and a surface pyrometer. Stringer beads were deposited the full length of the cracks. After welding, the casting was allowed to cool slowly, with asbestos packing around the weld area. The casting was stress relieved at 1100 F. Welds were machined.

Additional details of the welding procedure, as well as results of hardness tests taken after stress relief, are given in the table with Fig. 1.

Table 4. Effects of Welding Process, Preheat and Postheat on Hardness of Gray Iron (a)

Welding process	Preheat	Postheat	Brinell hardness: Base metal	Brinell hardness: Heat-affected zone
Gas(b) ..	None	None	167	277
Arc(c) ..	None	None	163	241
Gas(b) ..	500 F(d)	None	159	269
Arc(c) ..	500 F(d)	None	170	235
Gas(b) ..	None	1150 F	159	262
Arc(c) ..	None	1150 F	159	197

(a) Based on six specimens taken from a single heat with a composition of 3.46 C, 1.53 Si, 0.65 Mn, 0.096 P, 0.024 S. (b) With RCI filler metal. (c) Shielded metal-arc welding, with ENiFe-CI filler metal. (d) Higher preheat was not feasible because of small size of samples.

In addition to repair of defective or damaged castings, welding can be used to rectify production errors, as in the next example, in which a manufacturer of electric motors had to weld ribs omitted from cast motor frames in order to meet the production schedule for a specific line of motors.

Example 231. Alteration of Castings by Shielded Metal-Arc Welding (Fig. 2)

A tight production schedule on four motors was interrupted because the motor frames had been cast without ribs. Because the foundry was unable to supply replacements in less than three weeks, the motor manufacturer decided to correct the error by welding steel ribs to the frames, as shown in Fig. 2.

The ribs, 12 in. long, were cut from 1½-by-2-in. 1020 steel bar stock and tack welded in position. All surfaces to be welded were cleaned by sand blasting. Shielded metal-arc welding with 3/16-in. nickel electrodes (ENi-CI) was used to deposit ¼-in. fillet welds on all sides of the ribs. Welding current was 160 amp, 40 volts, dcrp. The castings were welded without preheat or postweld heat treatment. The only mechanical test of the welds occurred

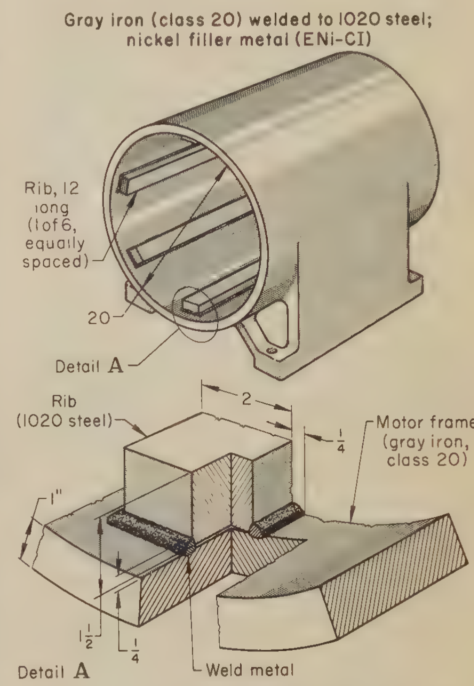
Table 5. Welding-Current Ranges for Shielded Metal-Arc Welding of Cast Iron With Nickel-Iron and Nickel Electrodes (a)

Electrode diameter, in.	ENiFe-CI electrodes(b): Current (dc), amp(d)	ENiFe-CI electrodes(b): Current (ac), amp	ENi-CI electrodes(c): Current (dc), amp(d)	ENi-CI electrodes(c): Current (ac), amp
3/32	40 to 70	40 to 70	40 to 80	40 to 80
1/8	70 to 100	70 to 100	80 to 110	70 to 110
5/32	100 to 140	110 to 140	110 to 140	110 to 150
3/16	120 to 180	130 to 180	120 to 160	120 to 170

(a) For welding in the flat position; current for overhead welding should be 5 to 15 amp less than shown; for vertical welding, 10 to 20 amp less. (b) Percentage composition, based on analysis of deposit on standard test pad: 2.00 C, 4.00 Si, 1.00 Mn, 0.03 S, 45 to 60 Ni, 2.50 Cu, 1.00 other, remainder Fe. (c) Percentage composition, based on analysis of deposit on standard test pad: 2.00 C, 4.00 Si, 1.00 Mn, 0.03 S, 8.00 Fe, 85 min Ni, 2.50 Cu. (d) Either polarity.

Table 6. Welding-Current Ranges for Shielded Metal-Arc Welding of Gray Iron With Cast Iron Electrodes

Electrode diameter, in.	Current (ac), amp
1/8	150 to 175
3/16	175 to 200
1/4	200 to 250



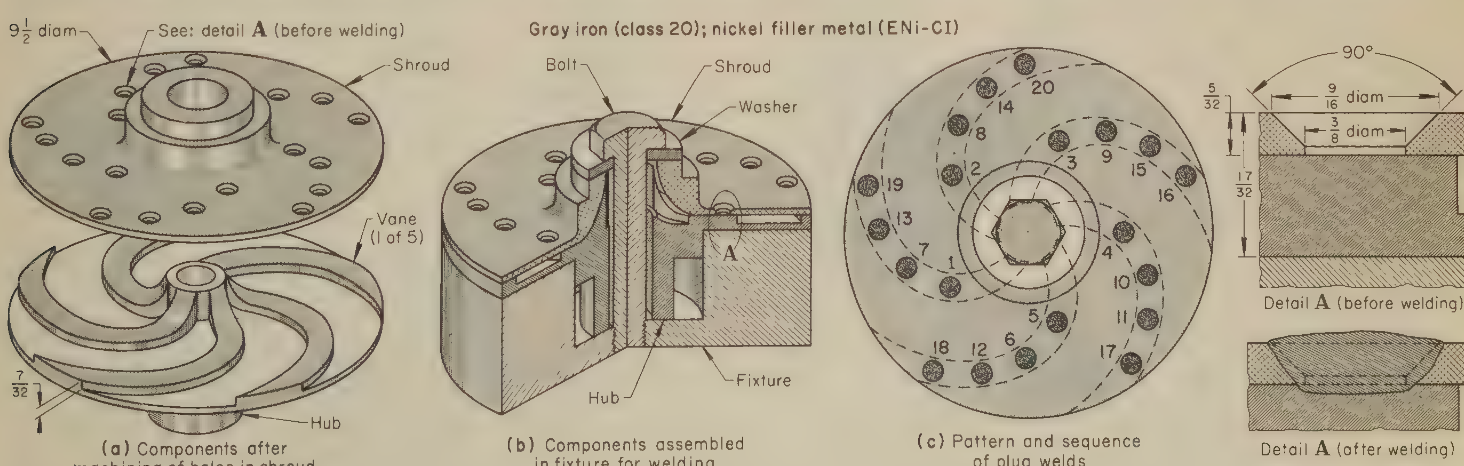
Cost of Altered Castings

Four castings	$307.36
Twenty-four ribs	19.52
Nickel electrodes	25.20
Labor and overhead	51.84
Total cost	$403.92
Alteration time	1 day

Cost of Replacing Castings

Four original castings	$307.36
Less scrap value	8.00
Net cost	$299.36
Four new castings	307.36
Total cost	$606.72
Replacement time	21 days

Fig. 2. Gray iron motor frame to which steel ribs were shielded metal-arc welded, to correct a production error (Example 231)



(a) Components after machining of holes in shroud

(b) Components assembled in fixture for welding

(c) Pattern and sequence of plug welds

Process ....Shielded metal-arc welding	Current ....110 amp, dcrp	Postheat ....None
Electrode ....1/8-in. ENi-CI(a)	Preheat ....None	Total time ....12 min per piece(b)

(a) This electrode contains approximately 99% nickel. (b) Total time for joint assembly and welding.

Fig. 3. Pump impeller cast in two pieces and joined by plug welding as shown, to avoid vane-passage obstructions encountered when impeller had been cast in one piece (Example 232)

during machining the inside diameter for stator clearance: each rib was struck more than 750 times as the boring tool was fed through the 12-in. rib length.

As the table with Fig. 2 shows, altering four castings by welding cost only 66% as much as replacement, and saved 20 days.

Welding can be used in the production of assemblies that require joining of cast iron to cast iron or to a dissimilar metal, often under special conditions. The two examples that follow illustrate this use of welding. In the first example, shielded metal-arc welding eliminated a casting problem. In the second, gas metal-arc and shielded metal-arc welding gave satisfactory results at the desired low cost.

Example 232. Shielded Metal-Arc Welding Cast Components of an Impeller Redesigned for Production as a Two-Piece Weldment (Fig. 3)

When impellers for high-pressure pumps were cast in one piece, they were frequently rejected because of obstructions in the vane passages. Pump performance was affected by even small obstructions, which were difficult to reach for repair. This problem was overcome by casting the impeller in two pieces (Fig. 3a), clamping the pieces in a fixture (Fig. 3b), and joining them with 20 plug welds (Fig. 3c, and detail A in Fig. 3).

Holes were drilled and countersunk in the shroud to give access to vane surfaces for plug welding (Fig. 3a). The components were degreased after machining, assembled in the fixture as shown in Fig. 3(b), and welded in the sequence given in Fig. 3(c).

The welds were required to withstand centrifugal forces created at 3600 rpm, and had to be machinable. Machinability was important because impellers of various diameters were made by turning down larger sizes. Shielded metal-arc welding, using a nickel electrode (ENi-CI), satisfied all requirements. Deposits of this electrode were found to be tough, yet machinable. Sequence welding distributed welding stresses evenly and resulted in better distribution of operating stresses. Additional welding details are given in the table with Fig. 3.

Example 233. Use of Gas Metal-Arc and Shielded Metal-Arc Welding for Joining Low-Carbon Steel to Gray Iron (Fig. 4)

Two welds were required on the class 30 gray iron sump base shown in Fig. 4. One joined the sump base to a low-carbon steel plate and the other joined a low-carbon steel oil-return tube to the sump base.

In joining the sump base to the low-carbon steel plate, gas metal-arc welding was used, because it was the lowest-cost process. Since this weld was noncritical, being used to hold the parts together to permit completion of the sump, the presence of hard constituents and cracks in the weld metal was of no consequence. As a result, the parts to be joined were not preheated or postheated. However, two sets of welding conditions were evaluated:

	Conditions 1	Conditions 2
Current, amp	120	150
Voltage, v	22.5	25
Wire-feed rate, ipm	340	400
Shielding gas (both)	96-97% A – 4-3% O_2	
Passes	Two	Two
Hardness, max, Rc	60-63	43-53

Microscopic examination of the welds made under both conditions showed the expected carbide in the fusion zone and martensite in both the fusion and heat-affected zones. Because Conditions 2 resulted in lower maximum hardness and better impact resistance, it was selected for production welding.

The oil-return tube was joined to the sump base before assembly because the joint was inaccessible after assembly. The shielded metal-arc process and an E7018 electrode were used for this weld.

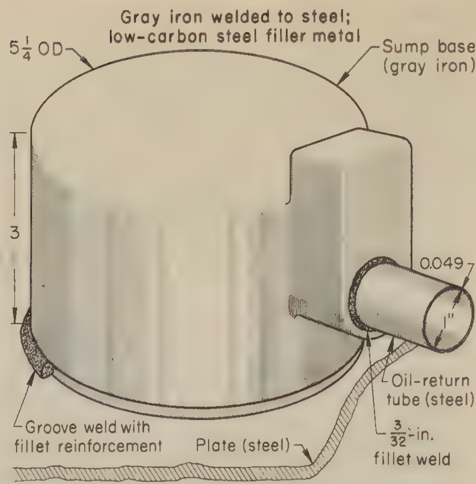
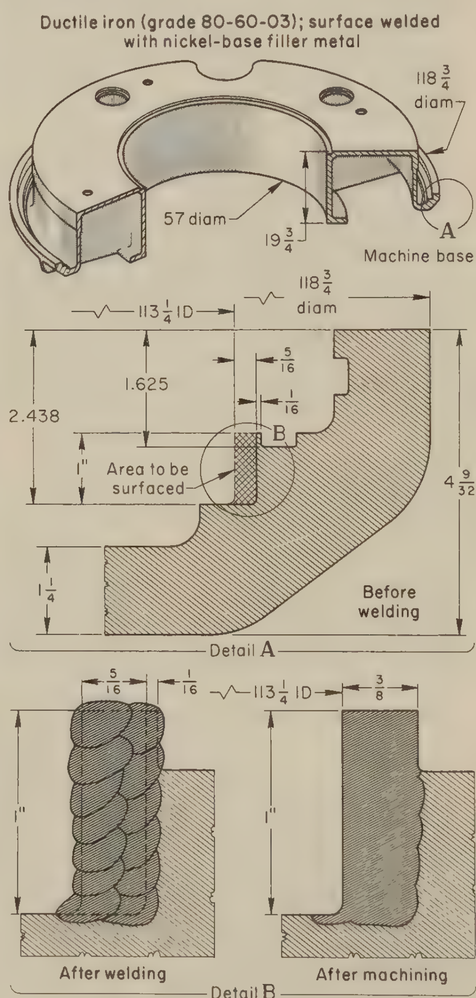


Fig. 4. Sump base that was gas metal-arc welded to a low-carbon steel plate, and to which a low-carbon steel tube was shielded metal-arc welded (Example 233)



Welding Conditions for Revised Procedure

Process	Shielded metal-arc welding
Electrode	5/32-in. proprietary
Position	Horizontal
Power supply	300-amp motor-generator
Current	120 amp, dcrp
Voltage	22 v
Sequence	Staggered, 12 in. on 24-in. centers
Preheat	Warmed to about 150 F
Postheat	None
Number of passes	About 13

Fig. 5. Ball-race section of a ductile iron machine base showing undersize area before and after welding (Example 234)

Ductile Iron

When pearlitic or ferritic ductile iron is welded, the heat-affected zone contains hard carbides and martensite, and so ductility, impact strength, and machinability are considerably reduced. Because the pearlitic types produce a larger amount of martensite in this zone, they are more susceptible to cracking, and are less weldable. These problems, however, do not preclude a useful service life for many kinds of pearlitic ductile iron weldments.

Preheating is desirable to reduce the possibility of cracking by reducing shrinkage stresses, but has little effect on the strength properties of the heat-affected zone.

Postweld heat treatments have some beneficial effect, but do not restore the original ductility of the heat-affected zone. Reheating at 1000 to 1200 F alters the hard martensite to tempered martensite. A full anneal is required to soften the heat-affected zone, but the original structure is not completely restored by this treatment. Some of the combined carbon, instead of forming large nodules, is broken down into small graphite particles that reduce ductility. Ferritic weld joints in grade 60-45-10 ductile iron have shown tensile strength well over 50,000 psi, with elongation up to 5% or slightly more. However, strength values obtained in testing ductile iron weldments are similar to those obtained in testing gray and malleable iron weldments, in that large variations are found in any group of test results.

Welding processes that have proved most successful on ductile iron are shielded metal-arc welding using an ENiFe-CI nickel-iron electrode, and gas welding with a ductile iron welding rod (see the article on Oxyacetylene Welding of Cast Irons, which begins on page 583 in this volume). With either process, joint preparation and joint cleanness require the same careful attention and are accomplished by following the same procedures as are described in the section "Preparation of Castings", on page 237 in this article.

Shielded metal-arc welding using an ENiFe-CI electrode is usually done with preheats of 300 to 400 F, although preheats up to, but not exceeding, 600 F have been recommended for large castings. In small or lightly stressed castings, preheat may not be necessary. The electrodes should be baked or otherwise kept dry, to help prevent underbead cracking of welds. Reverse-polarity direct current is used at an amperage sufficient to permit moderate welding speed, using stringer beads. If machinability or optimum joint properties are desired, the casting should be annealed immediately after welding.

Gas metal-arc welding (see page 78) is used in joining ductile iron. Examples 236 and 237 describe applications in which production welding required a semiautomatic or automatic method, and the gas metal-arc welding process was selected.

Repair welding is used on ductile iron castings, but correction of major surface defects by welding may create a new problem, as illustrated in the example that follows:

Example 234. Buildup of Undersize Surface on Ductile Iron Castings (Fig. 5)

The wall of a ball-race groove on a 118¾-in.-diam machine base for the rotary drive used in chemical and sanitary equipment was found, after six castings had been finish machined, to be only 1⁄16 in. thick instead of the required ⅜ in. thick (Fig. 5). Because the ductile iron bases were valued at about $1000 each as-machined, salvaging the castings was desirable. Shielded metal-arc welding was used to build up the undersize wall on one of the units, using an ENiFe-CI electrode. Subsequent machining of the weld deposit resulted in excessive tool wear and breakage, which were attributed to the hardness of the deposit. The fact that the 1⁄16-in. wall melted into the weld puddle may have contributed to high carbon pickup in the deposit and the high hardness.

A portion of the welding procedure was changed in repair welding of the five remaining castings. Shielded metal-arc welding was used, but:

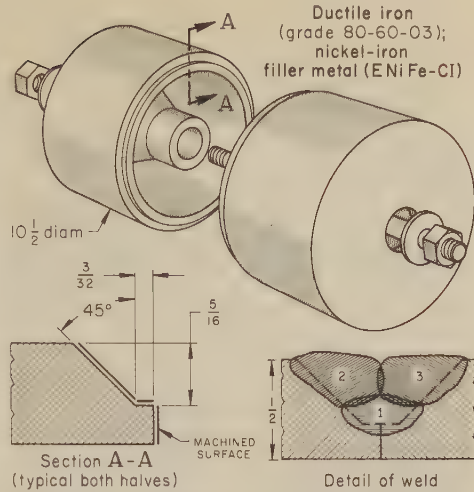
1 A proprietary electrode that contained a higher percentage of nickel was used. This electrode also had a specially formulated flux covering.
2 A block welding sequence was employed to reduce heat buildup and the attendant shrinkage stress.

Surface preparation involved wire brushing only, since the electrode covering was able to counteract the effect of limited amounts of surface contamination. Castings were warmed with a gas torch to about 150 F. With the castings supported for horizontal-position welding, a series of welds was deposited in blocks 12 in. long, staggered at 12-in. intervals.

In setting up the welding procedure, preheating of the entire casting, or even local preheating to a greater extent than the 150 F warming, was judged undesirable because of the size of the castings and the danger of distortion occurring in the many machined surfaces.

Reduction of hardness was the principal improvement sought. Hardness measured across the welds varied from 280 to 340 Bhn for the welds produced with the revised procedure, compared with an average hardness of about 370 Bhn, and hardnesses as high as 430 to 450 Bhn in many areas, for welds produced by the initial procedure. Additional details of the welding conditions for the ball-race groove are given in the table that accompanies Fig. 5.

Production arc welding of ductile iron is illustrated in the two examples that follow. In the first, manual welding by the shielded metal-arc process was used to simplify casting procedure and to save material.



Process	Shielded metal-arc welding
Electrode	ENiFe-CI(a), ⅛-in. for root pass; 5⁄32-in. for remaining passes
Number of passes	Three
Current	100 amp, dcsp
Power supply	300 amp, dc
Welding time	1st pass, 5 min; 2nd and 3rd passes, 6 min each
Position	Horizontal rolled
Preheat	1050 F
Postheat	(b)
Fixturing	Arbor-mounted and rotated in a lathe-type positioner

(a) Covered electrode with 55% nickel – 45% iron. (b) Heat to 1700 F, hold 4 hr, cool in air; heat to 1050 F, hold 5 hr, furnace cool to 550 F at 100 F per hour; then cool in air to room temperature.

Fig. 6. Ductile iron piston produced as a two-piece weldment (Example 235)

Example 235. Shielded Metal-Arc Welding of Ductile Iron Pistons With Nickel-Iron Electrodes (Fig. 6)

Pistons for low-speed high-pressure air compressors were originally cast in gray iron. When compressor speeds were increased, the need for a piston of lighter weight and higher strength was met by reducing wall thicknesses and casting the pistons in ductile iron. Changing to the two-piece design shown in Fig. 6 simplified casting procedures and permitted further weight reduction. Although aluminum pistons of this design were joined by epoxy bonding, reliable bonding of ductile iron was difficult to obtain, probably because of graphite on the joint surfaces. Shielded metal-arc welding with nickel-iron electrodes (ENiFe-CI) was finally selected, together with the following procedure.

Mating surfaces and weld bevels (Fig. 6) were machined without cutting fluid, and the piston halves were bolted together on an arbor and furnace heated to 1050 F. The preheated assembly was placed in an operator-controlled variable-speed positioning lathe, with the arbor horizontal. The partial-penetration groove weld was made in three passes (Fig. 6), and the assembly was then heat treated in a furnace to the desired strength range, corresponding to a hardness of 201 to 269 Bhn. Slag was removed and the weldment was finish machined to size.

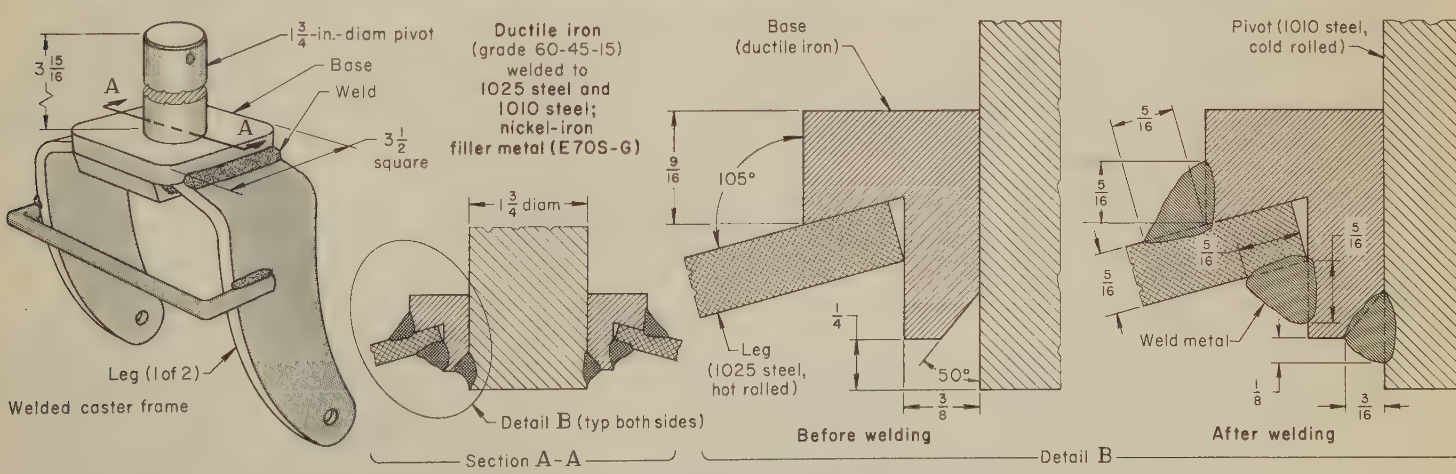
Because finished surfaces had to be free of any cracks, the welds were subjected to 100% magnetic-particle inspection. Small subsurface defects could be tolerated, because in operation the joint was required to develop only a small fraction of the nominal section strength of the base metal. Pistons up to 16 in. in diameter were produced, with weld rejection rates virtually nil. For additional welding conditions, see the table that accompanies Fig. 6.

Although shielded metal-arc and gas welding, when done by welders skilled in using these processes on cast iron, produce welds of excellent quality, automatic welding processes may be more economical in quantity production, as in the next example.

Example 236. Change to Semiautomatic Gas Metal-Arc Welding To Increase Production Rate (Fig. 7)

Caster frames for the front wheels of portable air compressors were made by welding the low-carbon steel and ductile iron assembly shown in Fig. 7 by the shielded metal-arc process. Manual welding was done using low-hydrogen electrodes (E7018, costing 29¢ per pound) without preheat. Production rate was approximately 24 pieces per 8-hr shift.

In an effort to improve efficiency, other welding methods were considered. Nickel-iron covered electrodes (ENiFe-CI) were recommended, and preheating was suggested. However, since the electrodes were expensive ($2.41 per pound) and the preheating operation was also costly, this recommendation was not adopted.



Conditions for Semiautomatic Gas Metal-Arc Welding

Electrode wire	0.045-in. diam, E70S-G	Fixture	Clamping jig	Number of passes per joint	One
Wire-feed rate	80 ipm	Current	200 amp, dcrp	Preheat and postheat	None
Shielding gas	75% CO_2 – 25% A	Voltage	26 v	Production per 8-hr shift	49 pieces

Fig. 7. Caster frame of ductile iron and low-carbon steel, for which production rate was doubled when semiautomatic gas metal-arc welding replaced a manual process, shielded metal-arc welding (Example 236)

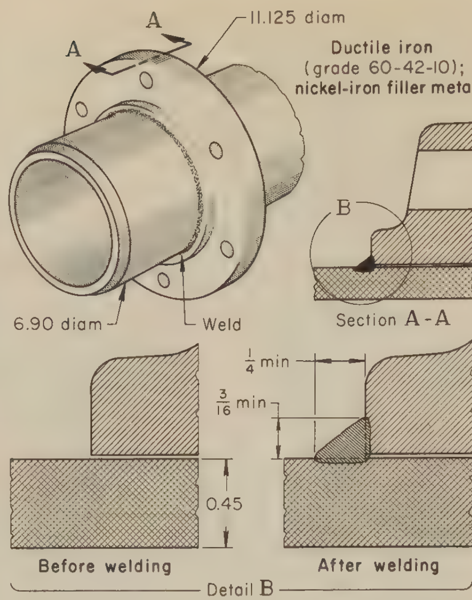
When gas metal-arc welding was investigated, it was found that semiautomatic welding could be done using a low-carbon steel electrode (E70S-G) costing only 32¢ per pound. Preweld cleaning and preheating were not necessary. In addition, welding was faster, flux removal was eliminated, and weld appearance was better. Parts were assembled in a fixture and tack welded, and each joint was welded in a single pass. Production rate increased to 49 pieces per 8-hr shift. The cost of filler metal and of shielding gas (75% carbon dioxide, 25% argon) was more than offset by the increase in production. Details of the welding procedure are given in the table that accompanies Fig. 7.

Shop vs Field Welding. Although field welding is satisfactory for many applications, shop welding is usually preferred when service requirements call for optimum weld properties. Besides allowing closer control over the welding operation proper, shop welding makes possible more effective use of preheat and postheat (which may be difficult, impractical, or hard to control in the field) and also allows the use of automated techniques not always possible in the field.

Example 237. Use of Gas Metal-Arc Welding in the Shop, Which Permitted Postweld Annealing Not Practical in Field Welding (Fig. 8)

Sections of ductile iron pipe, to one end of which ductile iron slip-on flanges had been fillet welded (see Fig. 8), and which were flared at the opposite end, were coupled by means of a lock joint. The slip-on flanges were gas metal-arc welded to the pipe sections in the manufacturer's plant. Each assembly was annealed after welding. The flanged sections were then assembled in the field and locked together by bolting. When necessary, some flanges were welded in the field, apparently with satisfactory results; but, since postweld annealing in the field was impractical, the heat-affected zones had lower corrosion resistance and toughness. This pipe installation was built for transporting water over mountainous terrain.

The shop welding procedure was essentially automatic. First, the joint surfaces were cleaned with detergent and ground to remove the casting skin. Next, the flange and pipe were mounted together on turning rolls under a stationary gas metal-arc welding head. To reduce the possibility of



Process	Gas metal-arc welding
Joint type	Lap
Weld type	Fillet
Preheat (flange only)	600 F
Electrode wire	0.045-in.-diam nickel-iron alloy(a)
Wire feed	432 ipm
Electrode holder	Machine type, water cooled
Shielding gas	Helium, at 30 cfh (or argon, at 20 cfh)
Welding position	Horizontal rolled
Current	200 amp, dcrp
Voltage	26 v
Number of passes	One
Power supply	200-amp rectifier
Welding speed	22 ipm (1 rpm)
Postheat	Ferritizing anneal(b)

(a) Coiled wire, nominally 55% nickel – 45% iron. (b) Heat to 1700 F in 15 min, hold at 1700 F for 15 min, cool to 1300 F in 15 min, air cool.

Fig. 8. Straight end of a ductile iron pipe section to which a ductile iron slip-on flange was fillet welded by the automatic gas metal-arc process (Example 237)

cracking in the ductile iron flange during cooling after welding, the flange (but not the pipe) was preheated to 600 F. Both the flange and the pipe were in the annealed condition.

After preheating, the flange was tack welded to the pipe in three places, using a nickel-iron electrode under helium shielding (argon was also used on occasion, but a sounder weld, free of any tendency to crack, was produced when helium was used). The electrode holder was then positioned at 45° from the vertical face of the flange, with the electrode aimed at a point about 1/16 in. from the flange, to ensure an even weld on both pipe and flange surfaces. Welding was done in a single pass, using the same electrode and shielding gas as for tack welding. (Other welding conditions are given with Fig. 8.) During welding, gas cup and contact tip were positioned as close to the work as possible, to increase arc efficiency and shielding coverage. After welding, the entire assembly was annealed. The procedure produced joint efficiencies approaching 100%.

Tests made on two-pass welded butt joints in the same pipe gave the following results:

Tensile Properties(a)		
Tensile strength	69,100 psi	
Yield strength	48,700 psi	
Elongation in 1 in.	19%	
Impact Properties(b)		
	At 70 F	At –40 F
Ft-lb, center of weld	14.9	13.3
Ft-lb, fusion zone	17.8	15.8

(a) Specimens measured 0.250 in. in diameter by 1 in. long. Tensile results are average values for ten specimens per weld. (b) Standard V-notch Charpy impact specimens.

Malleable Iron

During welding, the ductility of the heat-affected zone of malleable iron is severely reduced because graphite dissolves and precipitates as carbide. Although postweld annealing will soften the hardened zone, very little ductility is regained. Despite these limitations, for certain applications malleable iron castings are welded satisfactorily and economically if several precautions are followed. It is not recommended that malleable iron castings be welded to repair a failure caused by overstressing of the part.

Satisfactory welds have been obtained in arc welding malleable iron to steel where the joints were not to be severely stressed in service. Where the weld is to be subjected to fatigue of the type described in Example 240, stress should not exceed 10,000 psi.

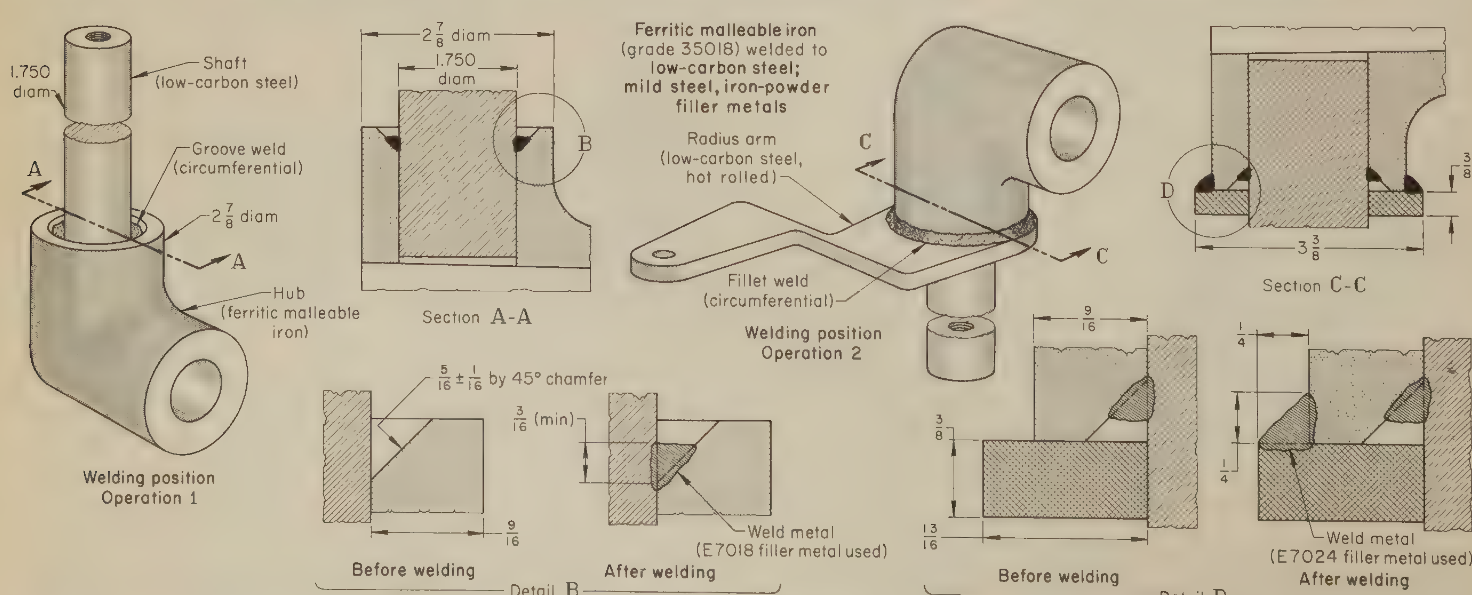


Fig. 9. Steering-knuckle assembly, and details of shielded metal-arc welds made to join the ferritic malleable iron and low-carbon steel components (Example 238)

If possible, welded joints should be loaded in compression, torsion or shear, rather than in tension or bending. With properly made welds, joint tensile strengths of 30,000 to 40,000 psi are obtainable.

Because most malleable iron castings are small, preheating is seldom used. If desired, small welded parts can be stress relieved at temperatures up to 1000 F. For heavy sections and highly restrained joints, preheating at temperatures up to 300 to 400 F and postweld malleablizing annealing have been recommended. However, this costly practice is not always followed, especially when the design of the assembly is based on reduced-strength properties of the welded joint. Because no welding procedure can satisfy all types of service conditions, each application for welding malleable iron assemblies should be carefully reviewed and tested before production is begun.

To avoid porosity and unnecessarily low joint strength, it is most important that the joint be cleaned before welding. Parts used in welded assemblies are usually machined at the joint to provide a suitable weld groove. Joints should at least be chipped or ground, the casting skin removed from the weld area, and the part thoroughly degreased with a solvent.

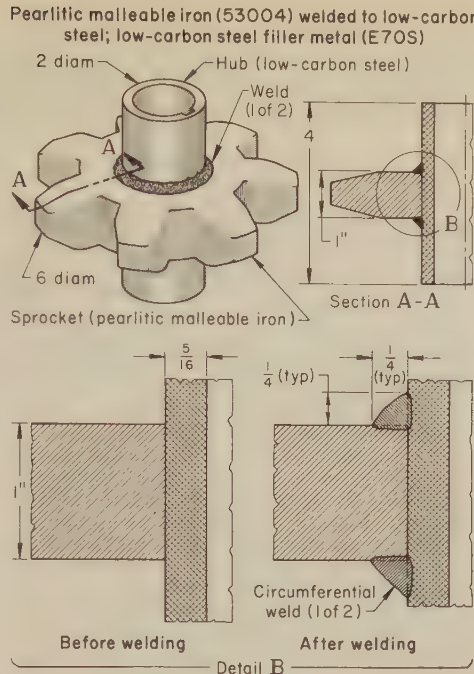
Ferritic malleable grades 32510 and 35018, although they lose some impact strength when welded, are the better welding grades of malleable iron. The pearlitic malleable irons, because of their higher combined carbon content, have lower impact strength when welded. Small leaks, gas holes, and other small casting defects can be repaired in grades 32510 and 35018 by arc welding. If it is necessary to machine a repaired area, arc welding should be done with nickel electrodes. If low-carbon steel electrodes are used, the part should be annealed to reduce any increased hardness in the weld (due to carbon pickup) and in the heat-affected zone.

Shielded metal-arc welding using low-carbon steel, low-hydrogen electrodes, at low amperage, has been used to produce satisfactory welds in malleable iron (see Example 238).

Gas metal-arc welding is better suited to producing welded assemblies of malleable and ductile irons than to general applications on gray iron. The important advantages of gas metal-arc welding, as compared with shielded metal-arc welding, are:

1. The amount of hydrogen in the vicinity of the gas-shielded arc is much less than that with flux-covered electrodes, and so welds made by this process are less susceptible to cracking.
2. Higher welding speeds reduce weld distortion.
3. Dilution of the weld metal is small; therefore, less carbon pickup can be expected.
4. The equipment is easily adapted to the welding of small assemblies.

In most applications, particularly where automation cannot be used to reduce labor cost, gas metal-arc welding is more expensive than shielded metal-arc welding, principally because of the high cost for the gas used. This



Process	Gas metal-arc welding
Electrode wire	0.045-in.-diam steel(a)
Shielding gas	Argon – carbon dioxide, at 15 cfh
Current	200 amp, dcrp
Voltage	28 v
Time per weld	About 15 sec

(a) Low-carbon steel deoxidized wire, corresponding to E70S types.

Fig. 10. Chain-drive sprocket made by welding a pearlitic malleable iron body to a low-carbon steel hub, using gas metal-arc welding (Example 239)

can be offset to some extent by the smaller amount of filler metal needed to fill the smaller joint grooves required by the gas metal-arc process.

The electrode wire usually recommended for use with gas metal-arc welding is a nickel-iron alloy having the same composition as the ENiFe-CI covered electrode used for shielded metal-arc welding. Low-carbon steel electrode wires have been used for joining malleable iron to low-carbon steel.

Submerged-Arc Welding. An application of joining malleable iron to low-carbon steel by submerged-arc welding is described in Example 241. However, submerged-arc welding has been used to a very small extent in welding any of the cast irons. The process generally is not suited to the repair of casting defects or damaged castings, because it requires unidirectional operation in the flat position. Other factors that limit its applicability are lack of visibility and high heat input.

Examples of Arc Welding Practice. The following four examples describe the welding of assemblies involving malleable iron and steel. Neither preheat nor postweld heat treatment was employed. Different arc welding processes were used with commercially available low-carbon steel electrodes in production welding setups. In each example, welding resulted in a low-cost assembly that adequately fulfilled service requirements. None of the welds was located in an area of the assembly that required machining.

Example 238. Shielded Metal-Arc Welding of Ferritic Malleable Iron to Steel (Fig. 9)

Part of the steering-knuckle assembly for 7-to-9-ton farm wagons consisted of a ferritic malleable iron hub to which a shaft and a radius arm, both of low-carbon steel, were welded (Fig. 9). In service, the two welded joints were subject to torsional shear stress, due to steering loads. A second shaft, which served as the wheel axle, was bolted to the hub. The hub was originally of cast steel, but malleable iron was substituted to reduce cost.

The weld groove was made by casting the hub with a 45° chamfer (Fig. 9). Preparation for welding consisted of shot blasting the malleable iron hub and degreasing the steel parts. There was no preheating and no postheating. Welding was done by the shielded metal-arc process, using low-carbon steel iron-powder electrodes. First, the vertical shaft was inserted in the hub and tack welded. This assembly was then mounted on a turntable and joined with a circumferential groove weld, using a 5/32-in. E7018 electrode at 90 amp, dcrp. To avoid interference with the radius arm, the groove was not completely filled. Next, the assembly was turned over and the radius arm was tack welded in position. Then, the arm and hub were joined with a circumferential 1/4-in. fillet weld, using a 1/8-in. E7024 electrode at 175 amp, dcrp. These welded joints have performed satisfactorily for several years.

Example 239. Joining Pearlitic Malleable Iron to Steel by Gas Metal-Arc Welding (Fig. 10)

Sprockets used for driving the digging chain of a trenching machine were made by welding low-carbon steel hubs to pearlitic malleable iron sprocket bodies (Fig. 10). This design combined good wearing qualities at the teeth with toughness in the keyseated hub. Production of these parts was simple, since no preheat and no postheat were used and no machining was required after welding.

The malleable iron castings were shot blasted, bored to size, and degreased. Premachined steel hubs were then tack welded in place, and the assembly was mounted on a turntable. The 1/4-in. low-carbon steel fillet welds deposited on each side were ample for the shear load on the sprocket, which was rated for 18 hp at about 260 rpm. Welding was done by the gas metal-arc process in a single pass, using relatively high amperage, voltage and welding speed, as shown in the table accompanying Fig. 10.

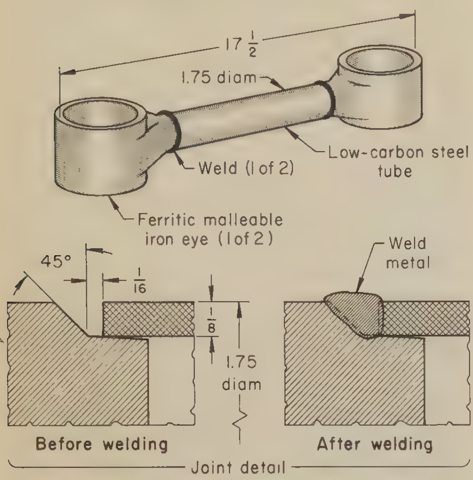
Originally, these sprockets had been welded by the shielded metal-arc process. With gas metal-arc welding, welds were cleaner, were deposited faster, were more uniform in appearance, caused less spatter, and produced fewer cracks. Although some cracking still occurred, it was not serious enough to interfere with the operation of the part, which had a good service record.

Example 240. Fatigue Strength of Gas Metal-Arc Welded Joints Between Ferritic Malleable Iron and Steel Tubing (Fig. 11)

Figure 11 shows a weldment on which fatigue tests were made to obtain data for use in production of welded malleable iron assemblies. The test piece, which consisted of two ferritic malleable iron eyes welded to a length of steel tubing, closely simulated an eye-bar or link commonly used to carry axial tension-compression loads. Accordingly, fatigue testing was done by applying full-cycle axial loads, alternately in tension and compression, at the rate of 120 full cycles per minute.

Before welding, the parts were cleaned with a solvent and assembled in a fixture rotating on a horizontal axis. As shown in Fig. 11, the weld groove was formed by the square end of the tubing and the 45° bevel machined on the plug end of the eye. The tapered plug end of the eye was inserted in the tube, and served as backing for the

Ferritic malleable iron (grade 32510) welded to low-carbon steel; 1% silicon mild steel filler metal



Conditions for Gas Metal-Arc Welding

Electrode wire	0.035-in.-diam E70S-6 type(a)
Wire-feed rate	298 ipm
Shielding gas	Carbon dioxide, at 15 cfh
Current	140 amp, dcrp
Voltage	23 v
Welding speed	13 ipm

Fatigue-Test Results

Max load, psi	Cycles to failure(b)
25,000	22,993(c)
25,000	66,352(c)
25,000	36,098(c)
25,000	46,892
20,000	72,403
20,000	139,394
20,000	244,347

(a) Composition: 0.11 C, 1.65 Mn, 1.12 Si, 0.021 P and 0.024 S. (b) Each cycle consisted of one axial load in tension and compression; 120 cycles per minute. (c) Failure occurred in eye of casting, not in weld.

Fig. 11. Gas metal-arc welded assembly of malleable iron and low-carbon steel, seven of which were used for preproduction fatigue testing (Example 240)

weld. The assembly was joined by gas metal-arc welding with carbon dioxide shielding gas and an electrode wire of the E70S-6 type (1% silicon, low-carbon steel), without being preheated. Seven test pieces were welded. The arc was held between 1 and 2 o'clock, and rotation was counterclockwise at 2.4 rpm. Other welding conditions are given in the table with Fig. 11, together with results of fatigue tests.

An eighth specimen was welded under the same conditions except that electrode wire composition was 0.12 C, 1.90 Mn, 0.80 Si, 0.020 P, 0.020 S, 0.50 Mo, and 0.10 Ni. This specimen failed after 8692 cycles at 18,000-psi tension and compression. Although the single test could not be conclusive, it suggested sensitivity to different steel electrode compositions.

Example 241. Submerged-Arc Welding of Ferritic Malleable Iron to Forged Steel (Fig. 12)

The snap coupler shown in Fig. 12 was used on various types of farm machinery as a power take-off. Because this part was impractical to make in one piece, it was produced by welding a ferritic malleable iron casting to the stub end of a forged steel universal joint. Ferritic malleable iron was used because it was less costly than steel and offered adequate strength. A 1/8-in. weld was sufficient to carry the service load.

Both mating surfaces were machined to form a stepped joint (Fig. 12) that provided good alignment and proper joint depth. The assembly was fitted over a spline that rotated on a horizontal axis. Submerged-arc welding was used with a low-carbon steel electrode wire and a standard flux, in a combination corresponding to AWS F62-EL12. The welding head was positioned near 12 o'clock, and welding was done in a single pass. Additional welding conditions are given in the table that accompanies Fig. 12. These snap couplers had a service-failure record of less than 0.1%.

Alloy Cast Irons

Alloy irons are used for service requiring resistance to abrasion, corrosion or heat. Some of these irons can be welded and some cannot.

Chilled and White Cast Irons. Both of these types of abrasion-resistant cast iron have structures free of graphitic carbon. Because of their extreme hardness and brittleness, they are generally considered unweldable.

Corrosion-Resistant Cast Irons. Alloys of this type are usually identified as high-silicon, high-chromium or high-nickel irons. Specifications for many of these irons permit welding for repair of minor casting defects. For more extensive welding, the effect on the service properties of the casting should first be determined, since applications of this group of cast irons are highly specialized. Because weld deposits must usually duplicate base-metal compositions, filler metals may not be generally available. Little information exists on welding procedures for these alloys.

Heat-resistant cast irons provide high strength at elevated temperature, as well as resistance to scaling. They are normally produced as flake-graphite irons, but may also be produced with the free carbon in the form of nodules or spheroids. The statements made in the paragraph above concerning the welding of corrosion-resistant cast irons apply to these irons as well.

Hard Facing

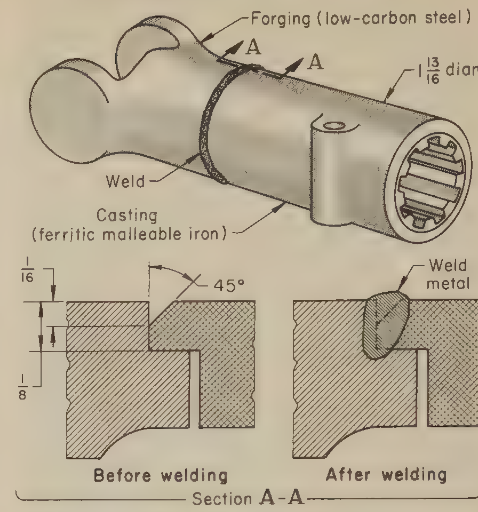
For two reasons, hard facing of cast iron is not generally recommended: (*a*) most cast irons (particularly gray iron) are highly susceptible to cracking from heating and cooling, thus requiring precise control over the hard facing operation; and (*b*) most cast iron parts are relatively inexpensive and are easily replaced, so that the cost of hard facing them is not usually justified unless it is outweighed by the cost of machine downtime required for replacement (see "Typical Application" at the bottom of the next column).

Preheating of castings to be hard faced is mandatory, to prevent cracking. For castings with uniform sections, 650 to 700 F is sufficient. For those with large differences in section thickness, 1100 to 1200 F is often used (dull red heat in normal room lighting). Higher preheating temperatures increase the amount of oxide formed, which impairs alloying. Time at the preheating temperature should be sufficient to ensure uniform heating.

"Buttering" with a buffer metal (one or more layers of type 310 stainless steel or a high-nickel alloy), although not mandatory, helps to prevent cracking of the base metal and provides a better bond between the hard facing alloy and the base metal.

Hard facing alloys that contain 2.5 to 4.0% carbon are generally used. The remainder of the alloy composition is

Ferritic malleable iron welded to low-carbon steel; mild steel filler metal (EL12)



Conditions for Submerged-Arc Welding

Filler metal	3/32-in.-diam EL12
Flux	F62
Current	275 amp, dcrp
Voltage	24 to 25 v
Preheat and postheat	None
Production rate	120 pieces per hour

Fig. 12. Snap coupler in which submerged-arc welding was used to join malleable iron to forged steel (Example 241)

chosen for the specific application. Several alloys of groups 3 and 4 (see Table 2 on page 155) are suitable. The alloy rods used for hard facing of cast iron are usually recognized by their graphite coatings. (For more information, see the article on Selection of Hard Facing Alloys, which begins on page 820 in Volume 1 of this Handbook.)

Manual arc welding is most often used, although when significant amounts of hard facing must be done the electrode holder may be mechanically held and guided.

Postheating is not ordinarily used, although slow cooling after hard facing is essential to prevent cracking. The hard faced casting may be placed in a furnace that is held at a temperature that approximates the preheating temperature. It must then be furnace cooled, although not necessarily right away. Often, several castings are hard faced and placed in the furnace before the cooling cycle begins.

If a furnace is not available, the hard faced casting may be buried in lime or other insulating material for slow cooling.

Typical Application. A manufacturer of bricks experienced severe wear on several cast iron machinery parts (pug-mill knives, sealing augers, shredder knives, barrel liners, and extrusion augers). This resulted in frequent and unscheduled downtime ranging from one to several hours, for replacement of the worn parts. Each hour of shutdown resulted in lost production of 10,000 or more bricks.

Hard facing of the machinery parts increased the wear life sufficiently to permit scheduled repair; no one part was kept in service long enough to wear severely.

Parts were preheated and hard faced by manual arc welding (essentially, shielded metal-arc), using a hard facing alloy composed of 3.2% C, 2.4% Si, 16.2% Cr and 0.74% Mo (a group 3 alloy). Hard faced parts were placed immediately in a furnace and cooled slowly in the furnace.

Arc Welding of Stainless Steel

*By the ASM Committee on Welding and Brazing of Stainless Steel**

ALL WELDABLE STAINLESS STEELS can be joined by the various arc welding processes but, because of the wide variations in composition and in physical and mechanical properties among the different types of stainless steel, they are not equal in weldability.

Gas tungsten-arc, plasma-arc, gas metal-arc, shielded metal-arc and submerged-arc welding are used extensively for joining stainless steel. Flux-cored arc welding is also used, but to a lesser extent. The various arc welding processes are not equally suitable for welding all stainless steels, because of differences in the compositions of the steels, and in fabricating conditions and end requirements.

This article discusses the weldability of the various grades, and the suitability of arc welding processes for specific conditions and requirements.

Austenitic Stainless Steels

Differences in composition among the standard austenitic stainless steels affect both their behavior in welding and performance in service. For example, types 302, 304 and 304L differ primarily in carbon content, and consequently there is a difference in the amount of carbide precipitation that can occur in the heat-affected zone after the heating and cooling cycle encountered in welding. Types 303 and 303(Se) contain 0.20% max phosphorus, plus 0.15% min selenium or sulfur, for free machining. These elements are detrimental in welding and can cause severe hot cracking in the weld metal. Types 316(Cb), 316L and 317 contain molybdenum, for increased corrosion resistance and higher creep strength at elevated temperatures, but during welding, molybdenum promotes carbide precipitation in the heat-affected zone unless restrained by an extra-low carbon content (as in type 316L). Types 318, 321, 347 and 348 are stabilized with titanium, or with columbium-plus-tantalum, to prevent intergranular precipitation of chromium carbides when the steels are heated to a temperature in the sensitizing range, as during welding.

Welding Characteristics. The austenitic stainless steels, except for the free-machining grades, are more weldable than the ferritic and martensitic stainless steels, and they provide welded joints that are characterized by a high degree of toughness, even in the as-welded condition. Satisfactory welded joints are readily obtained if the welding conditions adopted are compatible with the physical and mechanical properties of the steel. For example, the coefficient of thermal expansion of austenitic stainless steel is approximately 50% greater than that of carbon steel, whereas its thermal conductivity is only one-third that of carbon steel. In welding, these differences in physical properties significantly affect heat input and attendant warpage and distortion.

Effect of Carbide Precipitation on Corrosion Resistance of Welded Joints. The precipitation of intergranular chromium carbides is accelerated by an increase in temperature within the sensitizing range, and by an increase in time at temperature. When intergranular chromium carbides are precipitated at welded joints, resistance to corrosion and stress corrosion decreases markedly. The decrease in corrosion resistance is attributed to the presence of the chromium-rich carbides at the grain boundaries and the depletion of chromium in the adjacent matrix material. Although intergranular carbide precipitation generally takes place in the temperature range of 800 to 1600 F, sensitization is restricted to a narrower range by the fairly rapid heating and cooling that usually occur in welding. The narrower range varies with time at temperature and with steel composition, but is approximately 1200 to 1600 F.

The base metal immediately adjacent to the weld is annealed or solution treated by the heat of welding, and because it generally is cooled rapidly enough to hold the dissolved carbides in solution, this zone usually exhibits normal resistance to corrosive attack. A short distance from the weld, perhaps ⅛ in. (the distance depending on the thermal cycle), there is a narrow zone in which lower heating and cooling rates prevail. In this "heat-affected" zone, intergranular precipitation of chromium carbides is most likely to be encountered.

Prevention of Carbide Precipitation. Harmful carbide precipitation can be prevented by any of three methods: (*a*) solution heat treatment, (*b*) use of an extra-low-carbon (0.03% C max) alloy, and (*c*) use of a stabilized alloy containing preferential carbide-forming elements, such as columbium-plus-tantalum or titanium.

Solution heat treatment is a positive method for putting carbides back into solution and restoring normal corrosion resistance, but it is generally inconvenient and seldom entirely feasible. The solution-treating temperature range is very high — 1875 to 2050 F — and unless stainless steel is protected from air at these temperatures, it will oxidize rapidly, forming an adherent surface scale. Even when protected from air, thin sections, unless adequately supported, may sag or be severely distorted at these temperatures or during rapid cooling from them.

The need for rapid cooling in solution heat treatment may present problems. Water quenching, although effective, is seldom feasible except for small workpieces of simple configuration. Unless adequate safeguards are available, water quenching of large workpieces from a temperature in the range of 1875 to 2050 F is hazardous. Often, solution treatment is impractical because the workpiece is too large for available furnace and cooling facilities.

Extra-low-carbon stainless steels (types 304L and 316L) have enough immunity to carbide precipitation in the 800-to-1600-F temperature range to undergo normal welding or stress-relieving operations without impairment of corrosion resistance, but carbides will precipitate in significant quantities when extra-low-carbon steels are heated and held in the sensitizing temperature range for an extended period, as in service. These steels are generally recommended for use below 800 F.

Stabilized Steels. Compared with the extra-low-carbon steels, the stabilized steels exhibit higher strength at elevated temperature. For service in a corrosive environment in the sensitizing-temperature range (800 to 1600 F), an austenitic steel stabilized with columbium-plus-tantalum or titanium is needed. The filler metal used for welding should also be of a stabilized composition. Because an inert shielding gas is employed, gas tungsten-arc and gas metal-

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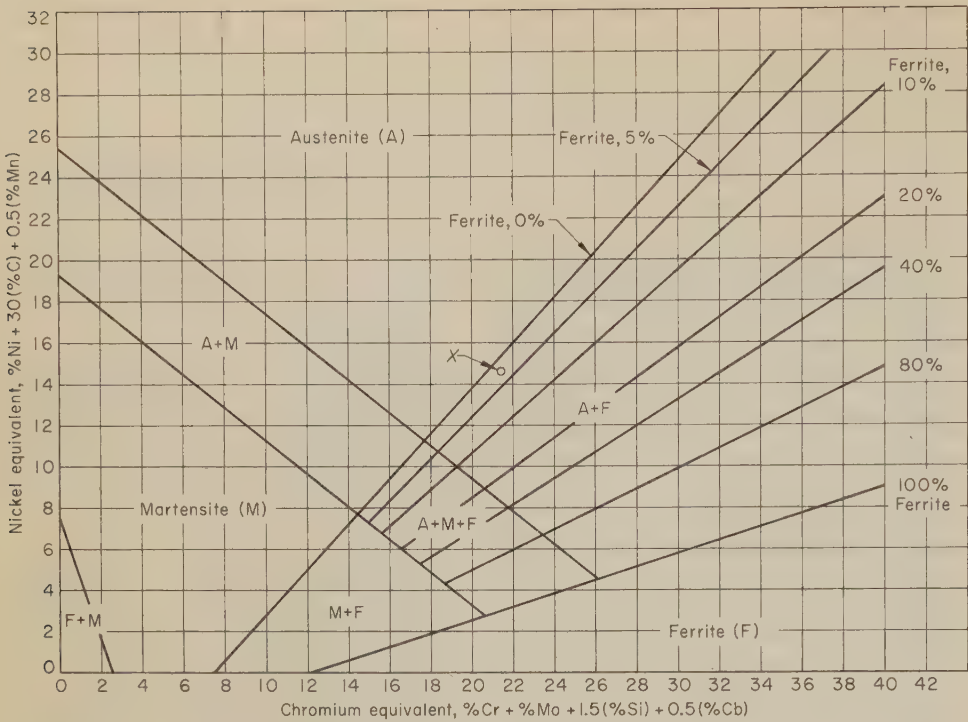
Many of the examples presented in this article were contributed by members of other Metals Handbook welding committees. Several sections of the article are based on an article by George E. Linnert and one by Raymond P. Sullivan, both in *Metals Engineering Quarterly,* November 1967, pages 1 to 15 and 16 to 41, respectively.



Example of Use. Point X on the diagram indicates the equivalent composition of a type 318 (316Cb) weld deposit containing 0.07 C, 1.55 Mn, 0.57 Si, 18.02 Cr, 11.87 Ni, 2.16 Mo, and 0.80 Cb. Each of these percentages was multiplied by the "potency factor" indicated for the respective element along the axes of the diagram, in order to determine the chromium equivalent and the nickel equivalent. When these were plotted as point X, the constitution of the weld was indicated as austenite plus from 0 to 5% ferrite; magnetic analysis of the actual sample revealed an average ferrite content of 2%.

For austenite-plus-ferrite structures, the diagram predicts the percentage ferrite within 4% for the following stainless steels: types 308, 309, 309(Cb), 310, 312, 316, 317 and 318.

Fig. 1. Schaeffler diagram for determining approximate amount of delta ferrite in the microstructure of austenitic stainless steel weld metal (Anton L. Schaeffler)

arc welding processes can be used to weld titanium-stabilized steel without oxidizing the titanium.

Under certain conditions, stabilized stainless steel weldments are susceptible to sensitization, which occurs in narrow zones of the base metal immediately adjacent to the line of weld fusion. Although during welding the carbides in the base metal adjacent to the weld are dissolved and, as a result of rapid cooling, are retained in solution, subsequent reheating to about 1200 F results in preferential precipitation of chromium carbides in a narrow, knifeline zone that exhibits less than normal corrosion resistance and that will corrode extensively in some mediums.

Microfissuring in Welded Joints. Intergranular cracking that results in the formation of microfissures in the weld metal or in the base metal near a welded joint is known as "hot cracking" or microfissuring. The occurrence of microfissuring is related to (*a*) the microstructure of the weld metal as-solidified; (*b*) the composition of the weld metal, especially the content of certain residual or trace elements; (*c*) the amount of stress developed in the weld as it cools; (*d*) the ductility of the weld metal at high temperatures; and (*e*) the presence of notches.

Susceptibility to microfissuring is highly dependent on the first of these factors — the microstructure of the weld metal. Weld metal with a wholly austenitic microstructure is considerably more susceptible to microfissuring than weld metal with a duplex structure of delta ferrite in austenite.

The content of alloying elements and residual elements strongly influences the susceptibility of fully austenitic stainless steel weld metal to microfissuring. Susceptibility can be reduced by a small increase in carbon or nitrogen content or by a substantial increase in manganese content. Residual or trace elements that contribute to microfissuring are, in approximate order of potency: boron, phosphorus, sulfur, selenium, silicon, columbium and tantalum.

It is important to minimize the amount of stress imposed on austenitic stainless weld metal as it cools from the solidus down to about 1800 F. It is in this temperature range that the weld metal is most susceptible to microfissuring, and if the level of stress is high, the fissures will propagate to form visible cracks. Peening is not an effective method of preventing this type of cracking, because it can seldom be applied early enough to reduce stress buildup in the temperature range concerned.

Prevention of Microfissuring. Either of two different practices is followed to prevent microfissuring, depending on whether weld metal with a duplex or a wholly austenitic microstructure is desired. To obtain duplex-structure weld metal that has controlled ferrite content (3 to 5% approximately), a filler metal of suitable composition is selected. Wide use has been made of the Schaeffler diagram (Fig. 1) to determine the amount of ferrite that will be obtained in austenitic weld metal of a given composition. Actual measurements of ferrite content can be made conveniently with the aid of a magnetic analysis device. Microfissuring can be prevented or minimized by proper control of ferrite in the weld metal — even when substantial dilution of weld metal with base metal occurs in the welding of free-machining austenitic stainless steels containing phosphorus and sulfur, or selenium.

Because many heats of austenitic stainless steel contain appreciable amounts of nitrogen — a very strong austenitizer — a revised constitution diagram for austenitic stainless steel weld metal has been developed to include nitrogen in the nickel equivalent (Fig. 2). This diagram is modified in shape and slope to improve the accuracy of ferrite estimation for types 309, 309(Cb), 316, 316L, 317, 317L and 318, compared with that obtained with Fig. 1. In addition, ferrite calculation for types 308 and 347 weld metals is improved on samples that contain either high or low nitrogen.

When it is required that the weld metal be wholly austenitic (as when the metal must be nonmagnetic), the content of crack-promoting residual elements must be stringently controlled, and the composition of the weld metal must be adjusted to increase crack resistance. Crack resistance can be increased by modifying the carbon, manganese, and nitrogen contents of the weld metal. However, even with optimum compositions and the most favorable welding procedures, wholly austenitic weld deposits will be more crack sensitive than those of a duplex structure.

Underbead cracking can occur in the heat-affected zone of the austenitic stainless base metal, immediately adjacent to the weld metal, especially in sections more than ¾ in. thick.

Serious failures due to underbead cracking have occurred in heavy-wall pressure vessels used in nuclear power units; the vessels were made of type 347 stainless steel, which is stabilized with columbium-plus-tantalum. Similar failures have occurred in thick-wall type 347 pipe used in high-temperature central steam stations; these failures occurred after seemingly sound welded joints had been subjected to high-temperature service for an extended period of time. The underbead cracking that caused the failures was attributed to strain-induced precipitation of columbium carbide, arising from shrinkage stresses in the heavy weldments.

Underbead cracking is not limited to columbium-stabilized steels. Tests have shown that all of the common austenitic stainless steels, with the possible exception of type 316L, are susceptible to this type of defect to some extent. Therefore, if underbead cracking is to be avoided, weld restraint must be kept to a minimum, especially in the welding of heavy sections.

Selection of Filler Metals. Electrodes and welding rods suitable for use as filler metal in the welding of austenitic stainless steels are given in Table 1. The notes in this table should be carefully studied before selection. (For AWS standard composition specifications for bare filler metals, see Table 6; Tables 11 and 12 list filler metals for gas metal-arc, submerged-arc and shielded metal-arc welding.)

Selection of filler metals for welding austenitic stainless steels requires consideration of the structural constituents of the deposited weld metal. Ultimately, these structural constituents determine the mechanical properties, crack sensitivity, and corrosion resistance of the weld. The constituents of principal concern are austenite, delta ferrite, and precipitated carbides.

Some filler metals, such as types 310, 310(Cb), 310(Mo) and 330, invariably deposit a fully austenitic weld metal. In these alloys, the ratio of ferrite formers to austenite formers cannot, within permissible limits, be raised high enough to produce any delta ferrite in the austenite. Consequently, when these filler metals are applied to restrained joints or to base metals containing additions of elements such as phosphorus, sulfur, selenium and silicon, only procedures proved suitable by experience should be employed.

The compositions of most filler metals are adjusted by the manufacturers to produce weld deposits that have ferrite-containing structures. Thus, ferrite-forming elements (such as chromium and molybdenum) are maintained at the high side of their allowable ranges, and austenite-forming elements (such as nickel) are kept low. The amount of ferrite in the structure of the weld metal depends on the ratio of "balance" of these elements.

At least 3 or 4% delta ferrite is needed in the as-deposited austenite for effective suppression of hot cracking. The ferrite is present in a dendritic pattern, because it is the primary phase in solidification. Ferrite-containing weld metal also combats the harmful effects of precipitated carbides on corrosion resistance, because carbides normally precipitate in and around the ferrite pools, instead of forming a continuous intergranular network.

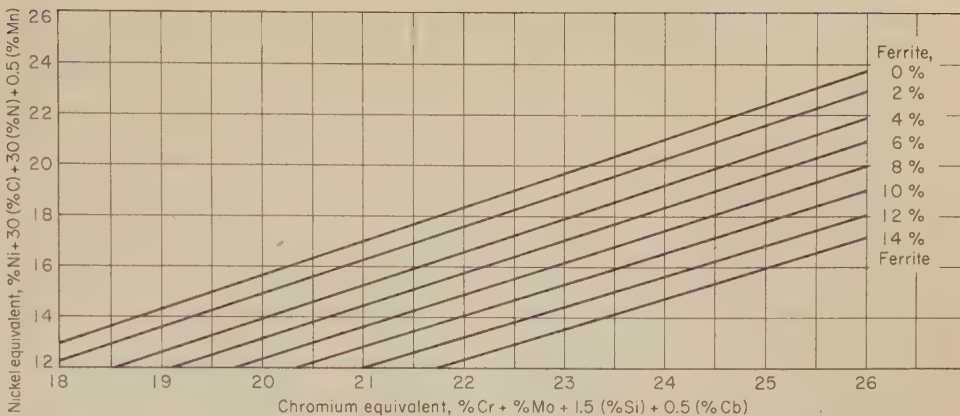


Fig. 2. Modified constitution diagram for austenitic stainless steel that includes nitrogen in the nickel equivalent (W. T. DeLong, G. A. Ostrom and E. R. Szumachowski, *Welding Journal*, Nov 1956, page 526s)

Ferrite-containing weld metal may have certain disadvantages in a welded austenitic stainless steel. Ferrite is ferromagnetic, and the increased magnetic permeability of the weld metal may be objectionable in applications that require nonmagnetic properties. When exposed to service at elevated temperature, the ferrite in some weld metals may transform to sigma phase and adversely affect mechanical properties and corrosion resistance, a problem that has been encountered in power-plant applications.

When a joint is arc welded without the addition of filler metal, the structure of the weld metal is determined by the composition of the base metal. Sometimes this leads to unfavorable results, because wrought base metals may not have the composition limits required for good weld metal.

Preheating. In general, no benefit is derived from preheating austenitic stainless steels. On the contrary, in some applications, preheating can increase carbide precipitation or cause shape distortion of the workpiece.

Postweld Stress Relieving. Although the effects of residual stress on the properties of austenitic stainless steels are limited in comparison with the effects of cold working, residual stress may significantly affect the mechanical behavior of an engineering structure. Because the effective yield strength varies from point to point, the application of further stresses at later stages of fabrication can cause excessive distortion and even premature failure. Nonuniform heating, which relieves some local residual stress, may also contribute to distortion. For these reasons, stress relieving may be required to ensure dimensional stability.

Stress relieving can be performed over a wide range of temperature, depending on the amount of relaxation required. Time at temperature ranges from about 1 hr per inch of section thickness at temperatures above 1200 F, to 4 hr per inch of section thickness

Table 1. Filler Metals (Electrodes or Welding Rods) Suitable for Use in Arc Welding of Stainless Steels

Type of steel welded	Condition of weldment for service(a)	Electrode or welding rod(b)	Notes (see below)	Type of steel welded	Condition of weldment for service(a)	Electrode or welding rod(b)	Notes (see below)
Austenitic Steels				**Martensitic Steels**			
301, 302, 304, 305, 308	1 or 2	308	(c)	403, 410, 416, 416(Se)	2 or 3	410	(k)
302B	1	309	(d)	403, 410	1	308, 309, 310	(m)
304L	1 or 4	347, 308L	...	416, 416(Se)	1	308, 309, 312	(m)
303, 303(Se)	1 or 2	312	(e)	420	2 or 3	420	(n)
309, 309S	1	309	...	431	2 or 3	410	(n)
310, 310S	1	310	...	431	1	308, 309, 310	(p)
316	1 or 2	316	(f)	**Ferritic Steels**			
316L	1 or 4	318, 316L	(f)				
317	1 or 2	317	(f)	405	2	405(Cb), 430	(q)
317L	1 or 4	317(Cb)	(f)	405, 430	1	308, 309, 310	(m)
318 [316(Cb)]	1 or 5	318	(f)	430F, 430F(Se)	1	308, 309, 312	(m)
321	1 or 5	347	(g)	430, 430F, 430F(Se)	2	430	(r)
347	1 or 5	347	(h)	446	2	446	...
348	1 or 5	347	(j)	446	1	308, 309, 310	(s)

SOURCE: George E. Linnert, Welding Characteristics of Stainless Steels, *Metals Engineering Quarterly*, Nov 1967

(a) 1 = as welded; 2 = annealed; 3 = hardened and stress relieved; 4 = stress relieved; 5 = stabilized and stress relieved. (b) Prefix E or ER omitted.

(c) Type 308 weld metal is also referred to as 18-8 and 19-9 composition. Actual weld analysis requirements are 0.08% max C, 19.0% min Cr and 9.0% min Ni. (d) Type 310 (1.50% max Si) may be used as filler metal, but the pickup of silicon from the base metal may result in weld hot cracking. (e) Free-machining base metal will increase the probability of hot cracking of the weld metal. Type 312 filler metal provides weld deposits that contain a large amount of ferrite to prevent hot cracking.

(f) Welds made with types 316, 316L, 317 and 317(Cb) electrodes or welding rods may occasionally display poor corrosion resistance in the as-welded condition. In such cases, corrosion resistance of the weld metal may be restored by the following heat treatments: for types 316 and 317 base metal, full anneal at 1950 to 2050 F; for types 316L and 317L base metal, 1600 F stress relief; for type 318 base metal, 1600 to 1650 F stabilizing treatment. Where postweld heat treatment is not possible, other filler metals may be specially selected to meet the requirements of the application for corrosion resistance.

(g) Type 321 covered electrodes are not regularly manufactured, because titanium is not readily recovered during deposition. (h) Caution is needed in welding thick sections, because of cracking problems in heat-affected zones. (j) In base metal and weld metal, for nuclear service, tantalum is restricted to 0.10% max, and cobalt to 0.20% max. (k) Annealing softens and imparts ductility to heat-affected zones and weld. Weld metal responds to heat treatment in a manner similar to the base metal. (m) These austenitic weld metals are soft and ductile in as-welded condition, but the heat-affected zone will have limited ductility.

(n) Requires careful preheating and postweld heat treatment to avoid cracking. (p) Requires careful preheating. Service in as-welded condition requires consideration of hardened heat-affected zones. (q) Annealing increases ductility of heat-affected zones and weld metal. Type 405 weld metal contains columbium rather than aluminum, to reduce hardening. (r) Annealing is employed to increase ductility of the welded joint. (s) Type 308 filler metal will not display scaling resistance equal to that of the base metal. Consideration must be given to differences in the coefficients of thermal expansion of the base metal and the weld metal.

at temperatures below 1200 F. Because of the high coefficient of expansion and the low thermal conductivity of austenitic stainless steels, cooling from the stress-relieving temperature must be slow.

The stress-relieving temperature selected must be compatible with the extent of carbide precipitation acceptable, and with the corrosion resistance desired. Nonstabilized steels cannot be stress relieved in the sensitizing-temperature range without sacrifice of corrosion resistance. Extra-low-carbon steels will be affected much less, because carbide precipitation in these steels is sluggish. Stabilized steels present no problem.

For austenitic stainless steels, the estimated percentages of residual stress relieved at various temperatures (for the times previously noted) are:

1550 to 1650 F ....85% stress relief
1000 to 1200 F ....35% stress relief

Examples of Welding Practice. Nineteen examples in this article deal with the arc welding of austenitic stainless steels. Table 2 identifies the steels and the welding processes employed, and relates them to the examples of specific applications.

Martensitic Stainless Steels

The standard martensitic stainless steels are types 403, 410, 414, 416, 416(Se), 420, 431, 440A, 440B and 440C. These steels derive their corrosion resistance from chromium, which they contain in proportions ranging from 11.5 to 18%. Steels with higher chromium content require a higher carbon content, to ensure the formation of martensite during heat treatment. The three type 440 stainless steels are seldom considered for applications that require welding, and filler metals of the type 440 compositions are not readily available.

Modifications of the standard martensitic steels contain additions of elements such as nickel, molybdenum, vanadium and tungsten, primarily to raise the allowable service temperature above the 1100 F limit for the standard steels. When these elements are added, carbon content is increased. With increasing carbon content, the problem of avoiding cracking in the hardened heat-affected zone of weldments becomes more serious.

Martensitic stainless steels can be welded in the annealed, hardened, and hardened and tempered conditions. Regardless of the prior condition of the steel, welding will produce a hardened martensitic zone adjacent to the weld. The hardness of the heat-affected zone depends primarily on carbon content of the base metal. As hardness increases, toughness decreases, and the zone becomes more susceptible to cracking. Preheating and control of interpass temperature are the most effective means of avoiding cracking. Postweld heat treatment is required to obtain optimum properties.

Preheating and Postweld Heat Treating. The usual preheating temperature range for the martensitic steels is 400 to 600 F. The carbon content of the steel is the most important factor in determining whether or not preheating will be necessary. On the basis of carbon content alone, a steel containing not more than 0.10% C seldom requires preheating, and one with more than 0.10% C requires preheating, to prevent cracking. Other factors that determine the need for preheating are the mass of the joint, the degree of restraint, the presence of a notch effect, and the composition of the filler metal.

The following guide can be used to correlate preheating and postweld heat treating practice with carbon contents and welding characteristics of martensitic stainless steels:

Carbon Below 0.10%. In general, neither preheating nor postweld annealing is required. Steels with carbon contents this low are not standard.

Carbon 0.10 to 0.20%. Preheat to 500 F, weld at this temperature, and cool slowly.

Carbon 0.20 to 0.50%. Preheat to 500 F, weld at this temperature, and anneal after welding.

Carbon Over 0.50%. Preheat to 500 F, weld with high heat input, and anneal after welding.

If the weldment is to be hardened and tempered immediately after welding, annealing may be omitted. Otherwise, the weldment should be annealed immediately after welding, without being allowed to cool to room temperature. The temperature ranges for subcritical and full annealing of the martensitic stainless steels are:

Type of stainless steel	Subcritical annealing, F	Full annealing, F
403, 410, 416	1350-1450	1550-1600
420	1375-1425	1600-1650
414	1225-1300	...
431	1150-1225	...
440A, 440B, 440C	1350-1450	1650

Filler Metal. Types 410 and 420 are the only standard martensitic stainless steels available in the form of bare or covered electrodes, for use as filler metal. This limitation is important when attempting to secure similar properties in both weld metal and base metal. Martensitic stainless steel weld metals are low in toughness in the as-deposited condition and are seldom placed in service without being heat treated to improve toughness.

Austenitic stainless steel filler metals are often used to weld the martensitic stainless steels. These electrodes or welding rods provide an as-welded deposit of somewhat lower strength, but of greater toughness, than the martensitic types. Filler metals suitable for welding some martensitic stainless steels are given in Table 1.

Example of Welding Practice. As noted in Table 2, Example 268 in this article describes an application of submerged-arc welding of martensitic stainless steel type 403.

Ferritic Stainless Steels

In general, the ferritic stainless steels are less weldable than the austenitic stainless steels. The ferritic steels also produce welded joints having lower toughness, because of grain coarsening that occurs at the high welding temperatures.

The standard ferritic stainless steels are: type 446 (25% Cr); types 430, 430F and 430F(Se) (17% Cr); and types 405 and 409 (13% Cr). Type 409 is ferritic because it has a low carbon content (0.08% max) and a minimum titanium content equal to six times the carbon content. Type 405, which also contains only 0.08% max C, contains an average of 0.20% aluminum, which is a strong ferrite former.

Effect of Welding Heat on Martensite Formation and Grain Coarsening. Although most ferritic stainless steels have compositions that ensure a ferritic structure at room temperature, variations in composition within the regular limits can result in the formation of small amounts of austenite during heating to elevated temperature. On cooling, the austenite transforms to martensite, resulting in a duplex structure of ferrite and a small amount of martensite. The martensite reduces both the ductility and the toughness of the steel. Annealing will transform the martensite and restore normal ferritic properties, but annealing increases cost and can result in an excessive amount of distortion — particularly in parts that were previously formed by a cold working process.

All ferritic stainless steel mill products are normally annealed at the mill to transform any martensite that may be present to a softer structure of ferrite and carbides. In this condition, the steel can be readily formed, bent or drawn. It is only when the steel is heated near or above the transformation temperature (approximately 1600 F), as during welding, that the risk of austenite formation (and subsequent transformation to martensite) arises. In addition, heating to temperatures above 1750 F results in enlargement of the ferrite grain size, which also reduces the ductility and toughness of the steel. Although martensite can be eliminated by annealing, coarsened ferrite grains remain unaffected. Because martensite responds to annealing and inhibits ferrite grain growth, some applications may benefit from martensite formation, provided that the workpiece can be annealed after welding. In a 17% chromium steel, martensite formation is promoted by lowering the chromium content to 15 or 16%. When this practice is adopted, it is usually necessary to preheat before welding or to select a steel of lower carbon content, in order to guard against cracking in the heat-affected zone.

When postweld annealing is not feasible, the ductility of the welded joint can be controlled by the selection of a stainless steel base metal containing a substantial amount of a strong ferrite former, such as aluminum, columbium or titanium. One such steel, which has the commercial designation of type 430(Ti), is a 17% chromium steel containing 0.12% max carbon and a minimum titanium content equal to six times the carbon content. The metallurgical functions of the titanium in this steel are to form stable titanium carbides and to promote the formation of ferrite. When a completely ferritic steel is welded, no martensite is formed in the heat-affected zone, although some grain coarsening may occur. Grain coarsening can be controlled to some extent by minimizing heat input during welding and by avoiding slow cooling from the welding temperature.

Effect of Temperature on Notch Toughness. For the 17% chromium steels, the temperature range for transition from a tough, shear-type fracture (at the higher temperature) to a brittle, cleavage-type fracture (at the lower temperature), upon impact at a notch, lies just above room temperature. Under impact loading at room temperature and below, these steels are notch sensitive, and impact-test values of less than 15 ft-lb are usual. At 200 to 250 F, the impact-test values increase to approximately 30 to 50 ft-lb.

This relation between notch toughness and temperature is important in the selection of joint design and welding conditions for ferritic stainless steel. In service, a weldment designed primarily to withstand static load may be subjected to accidental or unforeseen impact loading. Furthermore, a weldment with low notch toughness may not withstand appreciable multiaxial stresses even under a low rate of loading. Because multiaxial residual stresses are often developed during welding (especially when welding heavy sections), notches and points of stress concentration that might cause failure in service must be avoided whenever possible.

Because a relatively small increase in temperature greatly increases the toughness of the ferritic stainless steels, preheating before welding is often useful in preventing cracking during welding.

Preheating. The recommended preheating temperature range for ferritic stainless steels is 300 to 450 F. The need for preheating is determined to a large extent by the composition, mechanical properties, and thickness of the steel being welded. Steels less than ¼ in. thick are much less likely to crack during welding than those more than ¼ in. thick. However, other factors, such as the type of joint, joint location, restraints imposed by clamping and jigging, the welding process, and the rate of cooling from the welding temperature, can affect weld cracking (Example 251 describes an application in which crack-free welds were made in type 430 steel without preheating or postheating).

Postweld Annealing. The temperature range for postheating or postweld annealing of ferritic stainless steels is 1450 to 1550 F, which is safely below the temperatures for austenite formation and grain coarsening. Annealing transforms a mixed structure to a wholly ferritic structure and restores the mechanical properties and corrosion resistance that may have been adversely affected by the high temperatures encountered in welding. Thus, except for its inability to refine coarsened ferrite grains, annealing is generally beneficial. However, annealing has two major disadvantages: (*a*) the time and cost of the treatment; and (*b*) the need to prevent the formation of scale during heat treating, or to remove scale that does form. In addition, annealing may require the use of elaborate fixturing to prevent sagging or distortion of the weldment.

Cooling ferritic stainless steel from the annealing temperature may be done in air or by water quenching. To minimize distortion from handling, weldments often are allowed to cool to about 1100 F before they are removed from the furnace. However, slow cooling through the temperature range of 1050 to 750 F must be avoided, because it produces brittleness in the steel. Normally, susceptibility to this type of embrittlement, known as "885 F embrittlement", increases with increasing chromium content. Heavy sections may require forced cooling or a spray quench to bring them safely through this embrittlement range.

Table 2. Examples in This Article That Describe Arc Welding of Austenitic, Martensitic, Ferritic and Precipitation-Hardening Stainless Steels

Type of steel	Welding process(a)	Example
Austenitic Steels		
301 to AM-350	GTAW	261(b)
303 to low-carbon	GMAW	264(b)
304	GTAW	243, 245, 249
	GMAW	266
304 to 348 or Inconel 600	GTAW	270(b)
304L	GTAW	246
305 to 347	GTAW	262(b)
316	GTAW	253
316L	GTAW	258
321	GTAW	254, 263(c)
321 to 347	OAW to GTAW to GMAW(d)	265(b)
321 to low-carbon	GTAW	260(b)
347	GTAW	242, 255
	GTAW plus SMAW(e)	244
	SMAW plus SAW(e)	269
Martensitic Steel		
403	SAW	268
Ferritic Steels		
430	GTAW	251, 257
446	GTAW	252
Precipitation-Hardening Steels		
17-7 PH to AM-350	GTAW	256(b)
17-7 PH	GTAW	248
17-7 PH to 316L	GTAW	259(b)
PH 14-8 Mo	GTAW	250
PH 15-7 Mo	GTAW	247
AM-350 to 301	GTAW	261(b)
Cast Stainless Steel		
CD-4MCu to CD-4MCu	SMAW	267

(a) GMAW = gas metal-arc welding; GTAW = gas tungsten-arc welding; OAW = oxyacetylene welding; SAW = submerged-arc welding; SMAW = shielded metal-arc welding. (b) Welding of dissimilar metals. (c) Example deals with welding of type 321 to type 321, to alloy A-286, or to Inconel 718. (d) Progressive reselections of process. (e) For root pass and filler passes, respectively.

Selection of Filler Metal. As shown in Table 1, both ferritic and austenitic stainless steel filler metals are used in the arc welding of ferritic stainless steel. Ferritic stainless steel filler metals offer the advantages of having the same color and appearance, the same coefficient of thermal expansion, and essentially the same corrosion resistance as the base metal. However, austenitic stainless steel filler metals are often used to obtain more ductile weld metal in the as-welded condition.

Although austenitic stainless steel weld metal does not prevent grain growth and martensite formation in the heat-affected zone, the ductility of austenitic weld metal improves the ductility of the welded joint. However, the selection of austenitic stainless steel filler metal should be carefully related to the specific application, to determine whether differences in color or in the physical and mechanical properties of the weld metal and the base metal will cause difficulty.

For weldments that are to be annealed after welding, the use of austenitic filler metal can introduce several problems. The normal range of annealing temperature for ferritic stainless steels falls within the sensitizing-temperature range for austenitic steels. Consequently, unless the austenitic weld metal is of extra-low carbon content or is stabilized with columbium, tantalum or titanium, its corrosion resistance may be seriously impaired. Further, if the annealing treatment is intended to relieve residual stress in the weldment, it cannot be fully effective because of the difference in the coefficients of thermal expansion of the weld metal and the base metal.

Corrosion Resistance. Ferritic stainless steels are generally less corrosion resistant than austenitic stainless steels; therefore, any condition of the welded joint that might impair corrosion resistance must be avoided. The presence of martensite or the precipitation of sigma phase at the grain boundaries can cause severe intergranular corrosion in the heat-affected zone. Completely ferritic steels, such as types 430(Ti) and 446, display little or no susceptibility to intergranular attack at the welded joint. Annealing of any welded ferritic steel eliminates the unfavorable structural conditions that promote corrosive attack.

Examples of Welding Practice. As noted in Table 2, Examples 251, 252 and 257 in this article describe the application of gas tungsten-arc welding to ferritic stainless steels.

Precipitation-Hardening Stainless Steels

Designations and nominal compositions of typical precipitation-hardening stainless steels are given in Table 3. The steels are divided into three groups on the dual basis of characteristic alloying additions (particularly the elements added to promote precipitation hardening) and of the matrix structures of the steels in the solution-annealed-and-aged condition. Because these differences among the steels have a direct bearing on the behavior of the steels in heat treatment and in welding, the metallurgical characteristics of each of the three groups of steels are considered separately in the discussion that follows.

Martensitic Precipitation-Hardening (PH) Steels. These steels have a predominantly austenitic structure at the solution annealing temperature (1900 to 1950 F, approximately), but they undergo an austenite-to-martensite transformation when cooled to room temperature. The M_S temperature is usually in the range of 200 to 300 F.

Table 3. Nominal Compositions of Typical Precipitation-Hardening Stainless Steels

Common designation	AISI type	C	Cr	Ni	Mo	Cu	Al	Other
		Nominal composition, %						
Martensitic PH Steels								
Stainless W	635	0.07	17	7.0	...	...	0.2	0.7 Ti
17-4 PH	630	0.04	17	4.0	...	4.0	...	0.3 Cb
15-5 PH	...	0.04	15	5.0	...	4.0	...	0.3 Cb
PH 13-8 Mo	...	0.04	13	8.0	2.0	...	1.0	...
Semiaustenitic PH Steels								
17-7 PH	631	0.07	17	7.0	...	...	1.0	...
PH 15-7 Mo	632	0.07	15	7.0	2.0	...	1.0	...
PH 14-8 Mo	...	0.04	14	8.0	2.0	...	1.0	...
AM-350	633	0.08	17	4.0	3.0	...	...	...
AM-355	634	0.12	16	5.0	3.0	...	...	...
Austenitic PH Steels								
17-10 P	...	0.12	17	10.0	...	...	...	0.25 P
HNM	...	0.30	19	9.0	...	...	...	3.5 Mn, 0.3 P

When the martensite is reheated to 900 to 1100 F, precipitation hardening and strengthening occur, being promoted by the presence of one or more alloying additions — notably molybdenum, copper, titanium, columbium and aluminum. These elements and their compounds, which are dissolved during annealing and retained in solid solution by rapid cooling, produce a precipitate (usually, submicroscopic particles) that increases both the strength and the hardness of the martensitic matrix.

The compositional balance in the martensitic PH steels is critical, because relatively slight variations in composition can lead to the formation of excessive amounts of delta ferrite during solution annealing, or if the austenite is too stable, to the retention of large amounts of austenite at room temperature after solution annealing. Either of these two conditions will prevent full hardening during aging.

Welding Procedures for Martensitic PH Steels. These steels can be readily welded. The welding procedures employed resemble those ordinarily used for the series 300 stainless steels, despite differences in composition and structure between the two classes. The formation of martensite, which occurs during cooling from elevated temperatures such as those that occur in welding, does not result in full hardening. These steels are not sensitive to cracking and do not require preheating.

Selection of filler metal depends on the properties required of the welded joint. If strength comparable to that of the base metal is not required at the welded joint, a tough series 300 stainless steel filler metal may be adequate. When a weld having mechanical properties comparable to those of the hardened base metal is desired, the filler metal must be of comparable composition, although slight modifications are permissible to obtain better weldability.

When welds are deposited in a single pass, the weld metal and the heat-affected zone will usually respond uniformly to a postweld precipitation-hardening heat treatment; there is seldom any significant variation in hardness across the joint. Multiple-pass welds, however, exhibit a less uniform response to the same heat treatment, because successive applications of heat in welding result in marked variations in the structure of weld metal, heat-affected zone, and base metal. Annealing will eliminate these variations, and provide a more uniform structure capable of responding uniformly to precipitation hardening.

Semiaustenitic PH Steels. Unlike the martensitic PH steels, semiaustenitic PH steels are soft enough in the annealed condition to permit cold forming, drawing, rolling and spinning. When cooled rapidly from the annealing temperature to room temperature, they retain their austenitic structure, which displays good toughness and ductility in cold forming operations. The M_s temperatures for these steels are well below room temperature, but they vary, depending on composition and annealing temperature.

To obtain hardening and strengthening, the austenitic structure must be transformed to an essentially martensitic one. This can be accomplished by (*a*) heating the steel in the range of 1200 to 1600 F to precipitate carbides and other compounds, thus depleting the matrix of enough austenite-stabilizing elements to allow transformation of austenite to martensite when the steel is cooled to room temperature; (*b*) refrigerating the steel to a temperature well below the M_s point (−100 F, for example); or (*c*) cold working the steel enough so that the austenite transforms to martensite.

After transformation to martensite, the semiaustenitic PH steels respond to precipitation hardening in the temperature range of 850 to 1100 F in a manner similar to the martensitic PH steels. Whether a precipitate forms or a tempering reaction takes place depends on the steel composition.

The M_s temperature of the semiaustenitic PH steels is controlled by the solution annealing temperature, as well as by composition. For example, when AM-350 steel is solution annealed at temperatures below 1700 F, incomplete carbide solution results in raising the M_s temperature above room temperature. On the other hand, when the solution annealing temperature is raised above 1700 F, the M_s temperature drops precipitously. In practice, the solution annealing temperature is not permitted to exceed about 1925 F, because higher temperatures promote the formation of delta ferrite, which may increase the M_s temperature.

Welding Procedures for Semiaustenitic PH Steels. The semiaustenitic PH steels are normally welded in the annealed condition; the tough austenitic structure imparts welding characteristics similar to those of series 300 stainless steels. The semiaustenitic PH steels are not susceptible to cracking when welded, even when welded after transformation to martensite, because the low-carbon martensite developed is not of high hardness nor of low ductility. Also, cold cracking does not occur in the base metal adjacent to the weld, because the heat-affected zone is austenitized during welding and remains substantially austenitic as the joint cools to room temperature.

The choice of filler metal depends largely on the weld properties desired. The filler metal can be an alloy of precipitation-hardening composition capable of developing mechanical properties comparable to those of the base metal; or, if high strength is not a requisite, the filler metal can be a series 300 austenitic stainless steel.

When these steels are welded in the annealed condition, the following microstructural relations generally obtain as a result of relatively rapid heating and cooling at the joint:

1 The weld metal contains a small amount of ferrite in a matrix that is essentially austenite (hardness: approximately Rockwell B 90).
2 The base metal immediately adjacent to the weld displays a high-temperature annealed (austenitic) structure, having a hardness of approximately Rockwell B 90.
3 The base metal in a narrow zone just beyond the annealed zone next to the weld is hardened slightly (hardness: approximately Rockwell B 90 to 98).

If the welded assembly is given the customary double-aging heat treatment, the three areas identified above, as well as the unaffected base metal, will transform and precipitation harden uniformly to a hardness range commensurate with the precipitation-hardening temperature. The weld metal may be somewhat less tough than the wrought base metal (as measured by the results of tensile-elongation and bend tests), depending on the type of joint, the welding process, and the hardening temperature.

Higher precipitation-hardening temperatures will ensure good weld toughness with little sacrifice of strength. Maximum toughness requires annealing of the weldment prior to the transformation and hardening treatments. Although other variations in the welding and heat treating sequence are possible, and may be desirable at times, the choice of the sequence should be such that, after welding, the weld metal and the heat-affected zone are in the annealed (austenitic) condition. To harden these areas, both the transformation and the precipitation-hardening heat treatments must be applied. If the components are given the transformation treatment before welding, the precipitation-hardening treatment alone, after welding, will produce no significant hardening in either the weld metal or the heat-affected zone.

Austenitic PH Steels. The alloy content of these steels is high enough to maintain an austenitic structure after annealing, and after any aging or hardening treatment. The precipitation-hardening phase is soluble at the annealing temperature (2000 to 2050 F), and it remains in solution during rapid cooling from the annealing temperature. When these steels are re-

heated to about 1200 to 1400 F, precipitation occurs, and the hardness and strength of the austenitic structure increase. The hardness attained is lower than that of the martensitic or semiaustenitic PH steels, but the nonmagnetic properties are retained.

Welding of Austenitic PH Steels. Although the austenitic PH steels remain austenitic during all phases of forming, welding and heat treatment, some contain alloying elements (for precipitation-hardening purposes) that greatly affect behavior in welding.

The two austenitic PH steels listed in Table 3, 17-10 P and HNM, have very limited weldability; when heated above about 2150 F, they exhibit hot shortness because of the formation of phosphorus-rich compounds at the grain boundaries. When these steels are arc welded, hot shortness causes underbead cracking in the heat-affected zone. However, 17-10 P steel has been successfully flash welded, apparently because the upsetting force was adequate to extrude the hot short material in the form of flash and thus to produce a sound weld.

Examples of Welding Practice. Table 2 refers to six examples in this article on gas tungsten-arc welding of precipitation-hardening stainless steels.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding is adaptable to both manual and automatic operation, in all welding positions. The process can be used to produce continuous welds, tack welds, and spot welds, and it is capable of producing welds with or without filler metal.

The fundamentals of gas tungsten-arc welding, as they relate primarily to the welding of carbon and low-alloy steels, are covered in the article on Gas Tungsten-Arc Welding, which begins on page 113. Because this basic information applies to the gas tungsten-arc welding of all metals that can be welded by this process, including stainless steel, only those modifications that apply specifically to stainless steel are considered in this article.

Applicability to Stainless Steel. Gas tungsten-arc welding is particularly well suited to the welding of virtually all types and compositions of stainless steel, because: (*a*) the filler metal, when used, does not pass through the arc and, as a result, does not undergo significant alteration in composition; (*b*) the shielding atmosphere enveloping the arc is chemically inert, which eliminates the hazard of gas-metal reactions; and (*c*) no flux is used, so there are no slag-metal reactions and no nonmetallic inclusions. Transfer of elements from the filler-metal welding rod to the weld deposit is high, and the pickup of contaminants is extremely low. Because the properties and characteristics of stainless steels depend greatly on the maintenance of a preferred composition within close limits and on the avoidance of pickup of contaminants during the welding cycle, gas tungsten-arc welding is well suited to welding them, whether a filler metal is used or not.

Alloys Welded. Gas tungsten-arc welding can be applied to all weldable stainless steels, in both the wrought and cast forms, to clad products, such as stainless-clad carbon steel, and to dissimilar stainless alloys. The problems that may be encountered in welding certain alloys are not unique to gas tungsten-arc welding but rather reflect the specific weldability of the alloys. For example, the problem of how to avoid cracking in the hardened heat-affected zones of martensitic alloys becomes more serious with increase in carbon content. Selenium, which is added to certain alloys to improve their machinability, may prove troublesome in welding. These and other metallurgical considerations are discussed in the four preceding sections of this article, which deal with the welding characteristics of austenitic, martensitic, ferritic and precipitation-hardening stainless steels.

Work-Metal Thickness. For stainless steels, the gas tungsten-arc process is best suited, although not limited, to welding metal thicknesses of ¼ in. and less. Foil 0.002 in. thick has been welded successfully, using automatic equipment (see Fig. 18). In general, thicknesses from about 5⁄16 to ½ in. can be satisfactorily welded using multiple passes. Welding of sections thicker than ½ in. by the gas tungsten-arc process is usually ruled out because of high cost, but it may be used to obtain welds of high quality or to employ available equipment.

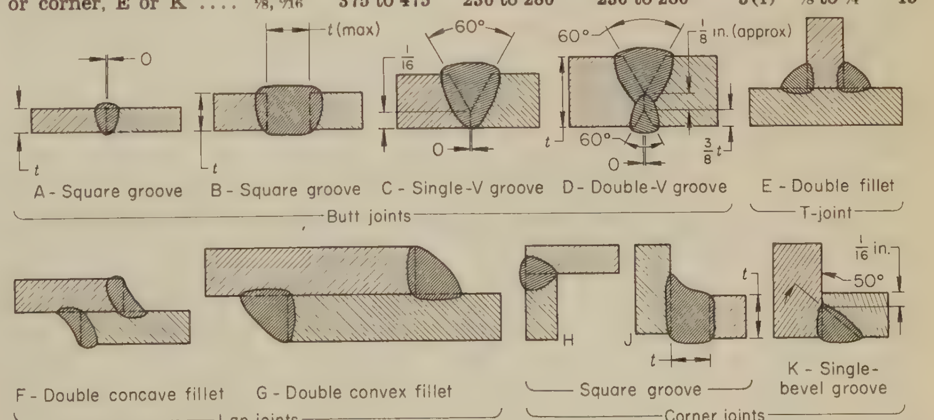
Workpiece Shape. Stainless steel imposes no limitations on workpiece shape that would not apply equally to the welding of carbon and low-alloy steels. General limitations are considered on page 113 in the article on Gas Tungsten-Arc Welding.

Welding Positions. Gas tungsten-arc welding of stainless steel can be performed manually in the flat, horizontal, vertical and overhead positions. Automatic out-of-position welding is possible with the use of special fixtures.

Current Characteristics. Although the general procedures for gas tungsten-arc welding of stainless steel are similar to those used for low-carbon ferritic steel, certain of the physical properties of stainless steel necessitate some alteration of current characteristics in welding. Specifically, the stainless alloys have higher thermal expansion and lower thermal conductivity, which increases the likelihood of distortion during welding. They also have

Table 4. Joint Designs and Operating Conditions for Manual Gas Tungsten-Arc Welding of Austenitic Stainless Steel

Type of joint and weld (see illustration)	Electrode diameter, in.	Welding current (dcsp), amp: Flat position	Vertical position(a)	Overhead position	Welding-speed(b), ipm	Welding-rod diameter(c), in.	Argon flow rate, cfh
1⁄16-In.-Thick Base Metal							
Butt, A or B	1⁄16	80 to 100	70 to 90	70 to 90	12	1⁄16	10
Lap, F or G	1⁄16	100 to 120	80 to 100	80 to 100	10	1⁄16	10
Corner, H	1⁄16	80 to 100	70 to 90	70 to 90	12	1⁄16	10
T or corner, E or J	1⁄16	90 to 100	80 to 100	80 to 100	10	1⁄16	10
3⁄32-In.-Thick Base Metal							
Butt, A or B	1⁄16	100 to 120	90 to 110	90 to 110	12	1⁄16, 3⁄32	10
Lap, F or G	1⁄16	110 to 130	100 to 120	100 to 120	10	1⁄16, 3⁄32	10
Corner, H	1⁄16	100 to 120	90 to 110	90 to 110	12	1⁄16, 3⁄32	10
T or corner, E or J	1⁄16	110 to 130	100 to 120	100 to 120	10	1⁄16, 3⁄32	10
⅛-In.-Thick Base Metal							
Butt, A or B	1⁄16	120 to 140	110 to 130	105 to 125	12	3⁄32	10
Lap, F or G	1⁄16	130 to 150	120 to 140	120 to 140	10	3⁄32	10
Corner, H	1⁄16	120 to 140	110 to 130	115 to 135	12	3⁄32	10
T or corner, E or J	1⁄16	130 to 150	115 to 135	120 to 140	10	3⁄32	10
3⁄16-In.-Thick Base Metal							
Butt, A or B	3⁄32	200 to 250	150 to 200	150 to 200	10	3⁄32, ⅛	15
Lap, G	3⁄32, ⅛	225 to 275	175 to 225	175 to 225	8	3⁄32, ⅛	15
Corner, H	3⁄32	200 to 250	150 to 200	150 to 200	10	3⁄32, ⅛	15
T or corner, E or J	3⁄32, ⅛	225 to 275	175 to 225	175 to 225	8	3⁄32, ⅛	15
¼-In.-Thick Base Metal							
Butt, B or C	⅛	275 to 350	200 to 250	200 to 250	5(d)	3⁄32 to 3⁄16	15
Lap, G	⅛	300 to 375	225 to 275	225 to 275	5(d)	3⁄32 to 3⁄16	15
Corner, H	⅛	275 to 350	200 to 250	200 to 250	5	3⁄32 to 3⁄16	15
T or corner, E or K	⅛	300 to 375	225 to 275	225 to 275	5	3⁄32 to 3⁄16	15
½-In.-Thick Base Metal							
Butt, C or D	⅛, 3⁄16	350 to 450	225 to 275	225 to 275	3(e)	⅛ to ¼	15
Lap, G	⅛, 3⁄16	375 to 475	230 to 280	230 to 280	3(f)	⅛ to ¼	15
T or corner, E or K	⅛, 3⁄16	375 to 475	230 to 280	230 to 280	3(f)	⅛ to ¼	15



SOURCE: R. P. Sullivan, Fusion Welding of Stainless Steel, *Metals Engineering Quarterly*, Nov 1967

(a) Current may exceed the ranges given. (b) For flat position only. (c) For welding-rod material, see Table 1. (d) Two passes may be needed. (e) Two or three passes may be needed. (f) For three passes.

Table 5. Summary of Operating Conditions for Gas Tungsten-Arc Welding of Stainless Steel From Examples in This Article

Example number	Base metal: Type of steel	Base metal: Thickness, in.	Electrode	Current (dcsp), amp	Voltage, v	Filler metal	Argon flow rate, cfh(a)	Welding speed, ipm
Manual Welding								
242	347	¼	EWTh-2	85, 100	12-15	ER347(b)	20	...
244(c)	347	0.50	EWTh-2	70	12	None	15-20	...
245	304	(d)	EWTh-1	34	15	None	15	2
246	304L	0.045, 0.090	EWTh-2	80-100	12-14	ER308L	15	2-4
249	304	0.109	EWP	70	14	ER308L	15	4
251	430	0.063	EWTh-2	31	...	ER430	5	...
258	316L	0.049	EWP	78	...	None	20	...
260	321 to carbon steel	0.014	EWTh-2	10, 55(e)	15, 9(e)	ER308L	10	(f)
263	321 to 321	0.032, 0.063	EWTh-2	80	10	ER347	10	3.25
	321 to A-286	0.093, 0.063	EWTh-2	130	10	ERNiMo-6	10	2.75
	321 to Inconel 718	0.188	EWTh-2	140	11-13	ERNiMo-6	20	3
270	304 to 348	(g)	...	110-130	12-14	ER308	10-15	12-18
Automatic Welding								
243	304	⅜	EWTh-2	190-220(h)	11	ER308L(j)	20	7
247	PH 15-7 Mo	0.040	EWTh-2	26-30	...	PH 13-8 Mo, ELC	(k)	...
	PH 15-7 Mo	0.050	EWTh-2	65-70	...	(m)	24	...
252	446	0.016	EWTh-2	60	8	None	12	(n)
253	316	0.093, 0.095	EWTh-2	105	15	ER316	(p)	12.75
254	321	0.034	EWTh-2	40	8	ER347	30	5
255	347	0.050	EWTh-2	73	7.5	ER347	60	4.5
256	17-4 PH to AM-350	0.020	...	14	16	None	(q)	5
257	430	0.024	EWTh-2	80	...	None	25	60
259	17-7 PH to 316L	0.002	EWP	30	7	None	15	7
261	301 to 301	0.028	EWTh-2	18.5	15	None	(r)	10
	301 to AM-350	0.028, 0.032	EWTh-2	50	15	ER308	(s)	10

(a) Information on backing and purging gases, when used, is included in the examples. (b) Type 347 consumable insert used for root pass. (c) Gas tungsten-arc welding used for root pass only. (d) 1⁄16-in. fillet weld through 1⁄32-in.-thick shoulder. (e) For first and second passes, respectively. (f) Ten joints per hour. (g) Type 304 baseplates ranging from 1¾ to 3½ in. thick were welded to 71⁄16-in. manifolds. (h) Different amperages between 190 and 220 for different passes. (j) Consumable insert ring of type 308L used for root pass. (k) Helium, at 120 cu ft per hour. (m) Consumable insert ring of PH 15-7 Mo, ELC. PH 13-8 Mo, ELC, wire added when needed. (n) 1000 pieces per hour. (p) Helium, at 45 cu ft per hour. (q) 75% helium and 25% argon, at 20 cu ft per hour. (r) Helium, at 30 cu ft per hour. (s) Helium, at 35 cu ft per hour.

Table 6. AWS Classifications and Composition Limits for Stainless Steel Filler Metals (AWS 5.9-69)

AWS classification	C	Cr	Ni	Mo	Mn	Si	P, max	S, max	Others
ER308(a)	0.08 max	19.5-22.0(b)	9.0-11.0	...	1.0-2.5	0.25-0.60	0.03	0.03	...
ER308L(a)	0.03 max	19.5-22.0(b)	9.0-11.0	...	1.0-2.5	0.25-0.60	0.03	0.03	...
ER309(a)	0.12 max	23.0-25.0	12.0-14.0	...	1.0-2.5	0.25-0.60	0.03	0.03	...
ER310	0.08-0.15	25.0-28.0	20.0-22.5	...	1.0-2.5	0.25-0.60	0.03	0.03	...
ER312	0.15 max	28.0-32.0	8.0-10.5	...	1.0-2.5	0.25-0.60	0.03	0.03	...
ER316(a)	0.08 max	18.0-20.0	11.0-14.0	2.0-3.0	1.0-2.5	0.25-0.60	0.03	0.03	...
ER316L(a)	0.03 max	18.0-20.0	11.0-14.0	2.0-3.0	1.0-2.5	0.25-0.60	0.03	0.03	...
ER317	0.08 max	18.5-20.5	13.0-15.0	3.0-4.0	1.0-2.5	0.25-0.60	0.03	0.03	...
ER318	0.08 max	18.0-20.0	11.0-14.0	2.0-3.0	1.0-2.5	0.25-0.60	0.03	0.03	(c)
ER320	0.07 max	19.0-21.0	32.0-36.0	2.0-3.0	2.5 max	0.60 max	0.04	0.03	(c) (d)
ER321	0.08 max	18.5-20.5	9.0-10.5	0.5 max	1.0-2.5	0.25-0.60	0.03	0.03	(e)
ER347(a)	0.08 max	19.0-21.5(b)	9.0-11.0	...	1.0-2.5	0.25-0.60	0.03	0.03	(f)
ER348	0.08 max	19.0-21.5(b)	9.0-11.0	...	1.0-2.5	0.25-0.60	0.03	0.03	(g)
ER349	0.07-0.13	19.0-21.5	8.0-9.5	0.35-0.65	1.0-2.5	0.25-0.60	0.03	0.03	(h)
ER410	0.12 max	11.5-13.5	0.6 max	0.6 max	0.6 max	0.50 max	0.03	0.03	...
ER420	0.25-0.40	12.0-14.0	0.6 max	...	0.6 max	0.50 max	0.03	0.03	...
ER430	0.10 max	15.5-17.0	0.6 max	...	0.6 max	0.50 max	0.03	0.03	...
ER502	0.10 max	4.5-6.0	0.6 max	0.45-0.65	0.6 max	0.25-0.60	0.03	0.03	...

(a) Available with a high silicon content (0.50 to 1.0%) and is so designated by an Si following the standard classification. (b) Chromium, (min), equals 1.9 times nickel, when so specified. (c) Columbium plus tantalum: 8 × C (min) to 1.0% (max). (d) 3.0 to 4.0% Cu. (e) Titanium: 9 × C (min) to 1.0% (max). (f) Columbium plus tantalum: 10 × C (min) to 1.0% (max). (g) Columbium plus tantalum: 10 × C (min) to 1.0% (max); tantalum max = 0.10%. (h) Tungsten, 1.25 to 1.75%; columbium plus tantalum, 1.0 to 1.4%; titanium, 0.10 to 0.30%.

generally lower melting points, which results in a slightly higher rate of weld-metal deposition for the same welding current.

Direct current of the constant-current (drooping-voltage) type, with straight polarity, is used, and the considerable heating effect produces a narrow, deep-penetration weld.

Although scratch starting may be acceptable in some applications, it can result in electrode contamination of the weld. For the same reason, and because of the possibility of carbon pickup, the arc must not be struck on a carbon block. High-frequency starting, which necessitates the use of a high-frequency generator to provide an ionized path for the welding current, is, therefore, most commonly used.

Table 4 shows ranges of welding current recommended for use in manual gas tungsten-arc welding of joints of several designs between stainless steel of various thicknesses, in the flat, vertical and overhead positions. These recommendations may be compared with the values for welding current shown in Table 5, which compares actual conditions reported for manual gas tungsten-arc welding in ten of the examples presented in this article.

Tungsten Electrodes. Of the five types of tungsten electrodes available for gas tungsten-arc welding, the most widely used for stainless steel is EWTh-2 (97.5% tungsten and 1.7 to 2.2% thoria). The thoriated electrodes are recommended because of their excellent emissive qualities. They may be used at higher current than pure tungsten electrodes, and they provide exceptional arc stability. The EWTh-2 electrodes are obtainable in standard diameters of 0.010 to ¼ in. Standard lengths generally used are 3, 6 and 7 in.

Contact between the end of the electrode and the molten stainless steel puddle may result in contamination of the weld metal, and this contamination may affect the properties of the weld metal adversely.

Shielding Gases. Depending on the application, argon, helium, or a mixture of argon and helium is used in the welding of stainless steel. The same gases may also be used for backing the weld. Argon is usually preferred, because it provides excellent protection at considerably lower flow rates. Furthermore, in welding thicknesses up to 1⁄16 in., there is less likelihood of burn-through when argon is used. Helium produces the higher heat input and deeper penetration required when welding thicknesses of more than about 1⁄16 in. On the other hand, the welding operation is usually easier with argon, especially in manual applications, because heat input to the weld puddle is less affected by variations in arc length. Finally, argon is less expensive than helium and is more readily available. However, as noted in Examples 247, 248, 253 and 261, helium is preferred as a protective gas or backing gas in some applications, and may be used with argon (as in Example 256).

Filler Metals for Gas Tungsten-Arc Welding

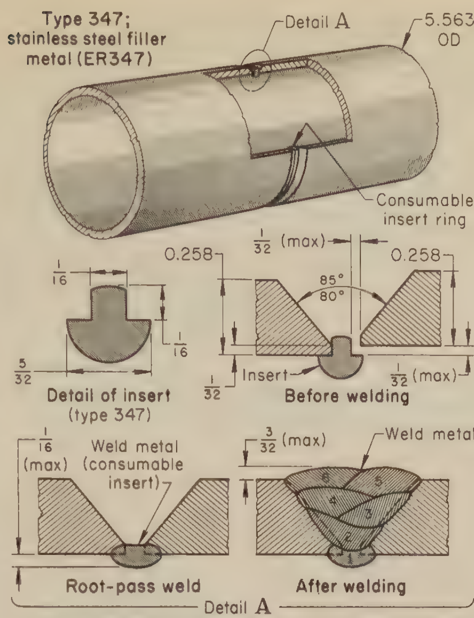
Bare stainless steel filler metals for use in gas tungsten-arc welding are covered by AWS specification A5.9-69. Designations and compositions of the filler metals are given in Table 6.

Sizes and Forms. Table 7 gives the standard sizes (diameters) of stainless steel filler metal in the three forms used in gas tungsten-arc welding of stainless steel — rod in straight lengths, wire in coils, and wire on 12-in.-OD spools. Normally, straight lengths are used in manual gas tungsten-arc welding, and coils and spools in automatic welding.

Selection of Filler Metal. It is evident from the filler-metal compositions listed in Table 6 that there are available filler metals that will deposit weld metal of compositions comparable with those of the standard wrought stainless steels. Generally, however, the problem of selecting a filler metal is not solved solely by matching alloy designations or compositions. Other factors, such as the interalloying of filler metal and base metal, filler-metal selection for welding dissimilar metals, and the metallurgical structure and properties of the weld deposit, must be considered. These factors are discussed in the sections earlier in this article that deal with the welding of austenitic, martensitic, ferritic and precipitation-hardening stainless steels. The filler metals suitable for welding similar stainless steels are given in Table 1; this table also lists the metallurgical condition in which the resulting weldment will be placed in service — a major consideration in the selection of filler metal. Table 8 shows filler metals suitable for welding joints in dissimilar austenitic stainless steels.

Use of Consumable Inserts. Consumable inserts offer an alternative method of supplying filler metal (*a*) when making the root pass in butt joints where accessibility is limited to one side of the joint, (*b*) where smooth, uniform, crevice-free contours are mandatory, or (*c*) where a root pass of highest quality is essential to the integrity of the completed weld. For pipe and tube joints, inserts are available in the form of rings of suitable diameter. Gas tungsten-arc welding results in the consumable insert being completely fused with the base metal.

Stainless steel inserts are of compositions formulated to promote weldability and to reduce the possibility of weld cracking. With inserts, smooth, uniform melting on pipe interiors is relatively easy to obtain, and weld contour appears to be relatively insensitive to welding variables.



Process ......Manual gas tungsten-arc welding
Joint type ....Circumferential butt
Weld type ....Single-V groove
Fixtures .....Turning rolls (shop); none (field)
Power supply ......300-amp motor-generator or transformer-rectifier
Electrode holder ....200 amp, water cooled
Electrode ....3/32-in.-diam EWTh-2(a)
Filler metal:
Root pass ....Type 347 consumable insert ring(b)
Filler passes ....3/32 and 1/8-in.-diam ER347
Shielding gas ....Argon, at 20 cfh(c)
Welding position ....Horizontal-rolled pipe (in shop)
Arc starting ....High frequency
Arc length ....3/32 to 1/8 in.(a)
Current (dcsp) ....Root pass, 85 amp; filler passes, 100 amp
Voltage ....12 to 15 v(a)
Preheat and postheat ....None

(a) For root pass and filler passes. (b) Containing 5 to 12% ferrite. (c) Argon, at 20 cfh, was also used for purging and backing.

Fig. 3. Nuclear-reactor pipe with a circumferential butt joint for which a consumable insert ring was used for the root pass, to ensure weld soundness (Example 242)

In joints that must satisfy high acceptance standards under visual, liquid-penetrant, and x-ray radiographic examination (as in the application described in the next example), the use of insert rings often serves to provide a root pass of highest quality. This benefit must be weighed against the cost of the insert rings and the extra labor cost for their installation.

Example 242. Use of Consumable Insert Rings in Welding 0.258-In.-Wall Type 347 Piping (Fig. 3)

Consumable insert rings were used for root-pass welding of circumferential butt joints in type 347 stainless steel piping. A typical joint, shown in Fig. 3, consisted of a single-V-groove with an insert ring fitted to the abutting ends of 5-in., schedule 40S (0.258-in. wall) piping. The piping was used in either the primary or secondary system of a nuclear reactor, and was required to withstand pressure of 2000 psi at an operating temperature of 600 F under water. The welded joints, therefore, had to meet rigid specifications, which included:

1 Complete joint penetration, with no notches at the root
2 Smooth inner surface, free from scale and oxides
3 Freedom from slag inclusions and cracks
4 Minimum porosity, as determined by radiographic inspection.

The manual gas tungsten-arc process was selected for welding the root pass, because of the reliability of the process in producing high-quality welds with smooth inner surfaces. The same welding process was used for the filler passes, because the wall thickness of the pipe was not great enough to warrant changing to another (and possibly more economical) process. The single-V-groove joint design was adopted because it was simple to prepare, afforded adequate access to the root of the joint, and did not require an excessive quantity of filler metal to make the weld.

The insert rings were of type 347 stainless steel modified to obtain 5 to 12% ferrite in the weld, to control microfissuring and cracking. The melting characteristic of the inserts, and the manner in which the weld puddle rose in the joint because of surface tension, enabled the welder to see exactly when the root pass had been properly made and the insert ring fused.

The bevels at the pipe ends for the V-groove were prepared either by machining or by careful grinding, within the dimensional tolerances shown in the middle right view in Fig. 3. Misalignments of the pipe ends and excessive root opening, which would have interfered with proper

Table 7. Standard Sizes of Filler-Metal Rod and Wire Used in Gas Tungsten-Arc Welding of Stainless Steel (AWS 5.9)

Form of filler metal	Diameter, in.(a)
Rod in straight lengths(b)	0.045, 1/16, 5/64, 3/32, 1/8, 5/32, 3/16
Wire in coils(c)	0.045, 1/16, 5/64, 3/32, 7/64, 1/8, 5/32, 3/16, 1/4
Wire on 12-in.-OD spools	0.030, 0.035, 0.045, 1/16, 5/64, 3/32, 7/64

(a) Tolerances are ±0.001 in. on diameters of 0.045 in. or less, and ±0.002 in. on diameters of 1/16 in. and larger. (b) Standard length is 36 +0, −1/2 in. (c) With or without support.

Table 8. Filler Metals Suitable for Welding Joints Between Dissimilar Austenitic Stainless Steels

	Suitable filler metals (listed in no preferred order; prefix ER omitted) — Base metal B (type of steel being welded to base metal listed in the first column)									
Base metal A(a)	304L	308	309	309S	310	310S	316,316H	316L	317	321,321H	347,347H 348,348H
304,304H,305	308L	308L	308,309	308,309	308,309,310	308,309,310	308,316	308,316	308,316,317	308	308
304L		308L	308,309	308,309	308,309,310	308,309,310	308,316	308L,316L	308,316,317	308L,347	308L,347
308			308,309	308,309	308,309,310	308,309,310	308,316	308,316	308,316,317	308	308,347
309				309	309,310	309,310	309,316	309,316	309,316	309,347	309,347
309S					309,310	309S,310S	309,316	309S,316L	309,316	309,347	309,347
310							310,316	310,316	310,317	308,310	308,310
310S							316	316	317	308,310	308,310
316,316H								316	316,317	308,316	308,316,347
316L									317	316L	316L,347
317										308,317	308,317,347
321,321H											308L,347

(a) The H suffix indicates a grade used for tubing for high-temperature service.

fusion, were avoided. The insert ring, in wire form, was carefully fitted and tack welded to the inside surface of one of the pipe sections, any overlap was trimmed off, and the ends were properly matched. The second pipe section was placed in position and aligned, and the complete assembly was held together by tack welds made at regularly spaced intervals.

Before making the root pass, the inside of the pipe was purged with argon, and the flow of argon was continued during welding, to provide backing gas and internal shielding. The general appearance of the root-pass weld is shown in the lower left view in Fig. 3. Filler passes were made with ER347 welding rods 3/32 and 1/8 in. in diameter. A cross section through the completed joint, showing the number of filler passes, is shown at lower right in Fig. 3. Welding conditions for the root pass and filler passes are given with Fig. 3.

After each operation (root pass and filler passes), welds were closely inspected by visual and liquid-penetrant techniques. The completed weld was then subjected to radiographic examination.

The production of nuclear reactor components required the welding of two circumferential butt joints in stainless steel pipes that, when assembled, served as a housing for drives. This nuclear application imposed rigid acceptance standards on weld quality, pipe alignment, and over-all dimensional tolerances. These standards were met by using consumable inserts and automatic welding, as described in the following example.

Example 243. Use of Consumable Inserts in Automatic Welding of 20-Ft-Long Tubular Housings (Fig. 4)

Housings for nuclear reactor components were produced as welded assemblies of type 304 stainless steel pipe sections ranging from 4 to 8 in. in outside diameter. Figure 4 shows a typical housing, 20 ft long, made up of two pipe sections tapered from 6-in. to 5-in. OD (pipes A and C) butt welded to the ends of a 5-in.-OD pipe (pipe B); all three components had a 3/8-in. wall thickness. The housing was required to be straight within 1/32 in. over the 20-ft length, and the welds had to meet stringent standards for soundness. Maintaining alignment and straightness was the major difficulty encountered during welding. To obtain ample control over all the welding conditions, an automatic welding procedure was developed. This incorporated the use of a consumable insert ring of inverted-T shape for the root-pass weld in each joint.

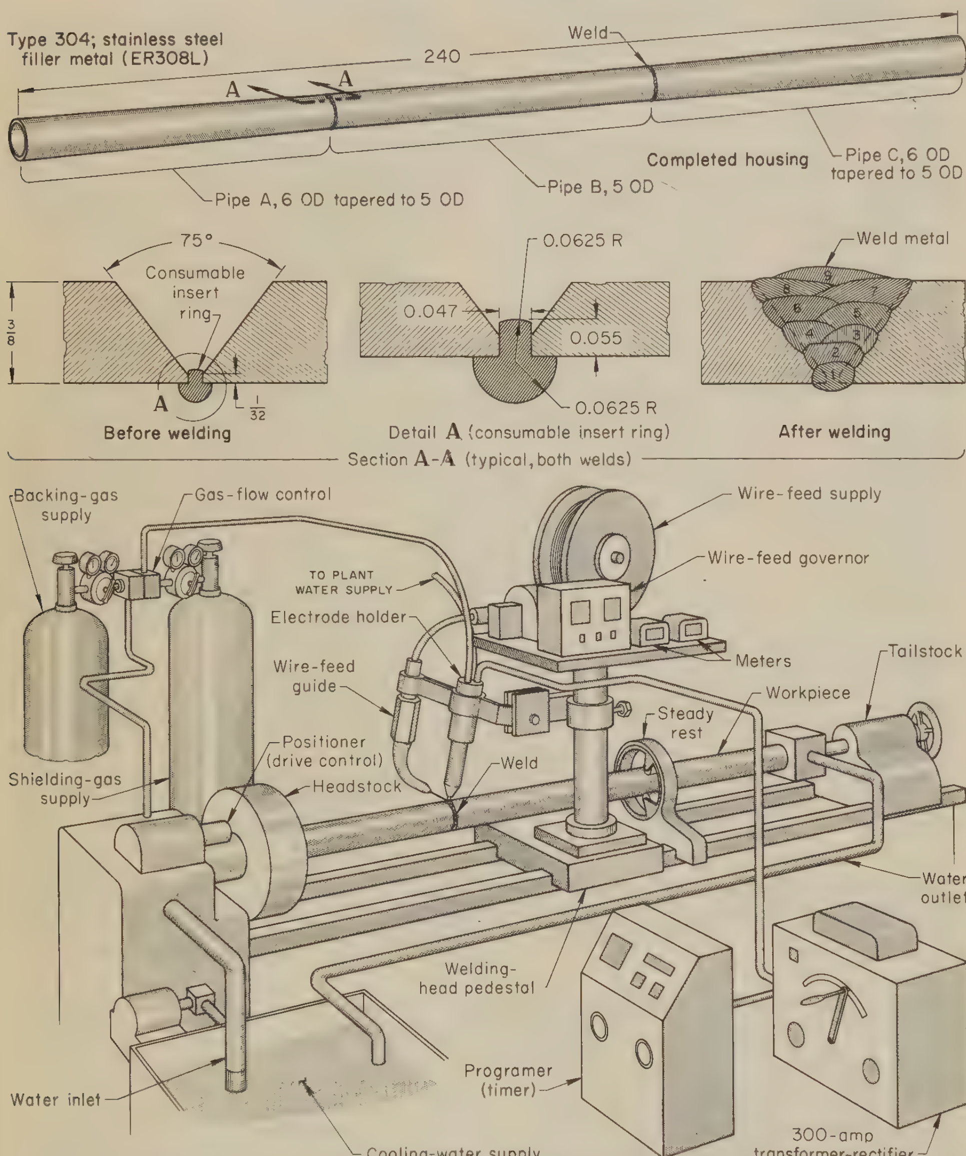
Equipment for the welding procedure (see bottom view in Fig. 4) was built around a large lathe bed that had been modified to support an automatic gas tungsten-arc welding head and wire-feed drive on the lathe carriage. A special drive, installed at the headstock, was controlled electronically by tachometer feedback to maintain less than 1% variation in the rotational speed of the pipe. Provision was also made for automatic control of (*a*) flow of shielding gas at the torch and for purge backing inside the pipe; (*b*) flow of cooling water at the torch, with optional flow inside the pipe; and (*c*) coordinated filler-metal feed, when required. The use of purge backing inside the pipe was restricted to the first three passes; when needed, water was used as coolant during the remaining passes.

Power was supplied by a 300-amp transformer-rectifier equipped with upslope and downslope current control and with provision for high-frequency arc starting. An automatic sequence timer (programer) controlled cycle timing (see item 16 in the list of operations, below) for each pass.

As shown in section A-A in Fig. 4, each butt joint had a 75° V-groove, and was designed with a 1/32-in. root face and a 0.047-in. root opening to accommodate a consumable insert ring. Although the base metal at the joint was only 3/8 in. thick, eight filler passes were specified, to avoid excessive heat input, which could result in distortion. Heat buildup was further controlled by establishing a maximum interpass temperature of 350 F. Cooling water was circulated inside the tubular housing during the last six filler-pass welds to cool the joint rapidly and prevent significant carbide precipitation in metal that had been heated in the sensitizing-temperature range (800 to 1600 F).

Machine settings and other welding conditions are summarized in the table that accompanies Fig. 4. The sequence of operations for welding, and the quality-control methods used, are listed below:

1 The edges of the pipes to be welded were beveled by machining; joint areas were cleaned by brushing with stainless steel brushes that had not been used on metals other than 18-8 stainless steel.
2 Pipe A was chucked in the headstock, using a dial indicator to verify accuracy of alignment.
3 Pipe B was placed in the steady rest, and the tailstock was advanced until pipes A and B were properly positioned; the dial indicator was used to check alignment. Tailstock was retracted.



Process	Automatic gas tungsten-arc welding	Welding position	Horizontal-rolled pipe
Joint type	Circumferential butt	Arc starting	High frequency
Weld type	Single-V groove	Arc length	3/32 ± 1/32 in.
Power supply	300-amp transformer-rectifier(a)	Current (dcsp):	
Auxiliary equipment	Sequence timer(b)	Passes 1 and 2	190 amp
Electrode holder	300 amp, water cooled(c)	Pass 3	200 amp
Electrode	1/8-in.-diam EWTh-2(d)	Passes 4 and 5	210 amp
Filler metal:		Passes 6 and 7	220 amp
Root pass	Consumable inverted-T-shape insert ring, type 308L	Passes 8 and 9	215 amp
Passes 2 to 9	0.035-in.-diam ER308L	Voltage (all passes)	11 v
Shielding gas:		Filler-wire feed rate	45 ipm
At torch	Argon, at 20 cfh	Preheat, postheat	None
Purge backing	Helium, at 10 cfh	Interpass temperature	350 F max
		Welding speed	7 ipm

(a) With high frequency, upslope and downslope control, and remote-control panel. (b) For programing and presetting of gas preflow and postflow, wire feed and weld time. (c) Machine type with gas lens, 1/2-in.-diam cup. (d) Tapered to 0.010-in. diameter over a 1/4-in. length at tip.

Fig. 4. Housing for a nuclear-reactor component (top) that was welded in the lathe setup shown, to maintain critical alignment, and for which consumable insert rings were used for root passes, to ensure weld soundness (Example 243)

4 The flow of purging gas was started and maintained for 5 min before welding began.
5 A consumable insert ring was tack welded in four places at 90° intervals to the joint face on pipe A.
6 Tack welds were wire brushed with a stainless steel brush.
7 Alignment was rechecked.
8 Buildup from tack welds was removed.
9 Tailstock was advanced to butt pipes A and B.
10 Midway between the original tacks, pipe B was tack welded to the insert. Tacks were continued across the insert to include pipe A.
11 Tack welds were wire brushed with a stainless steel brush.
12 Alignment was rechecked.
13 Buildup from tack welds was removed.
14 Welding cycle was started for the root pass (fusion of the insert ring).
15 The first pass was wire brushed when the pass was completed.
16 The headstock was turned 360°, while alignment was checked with a dial indicator. When the high point was reached, the headstock was turned 20°, and the second pass was started. This procedure was repeated after each pass. Typical cycle times for the 5-in.-OD pipe were:

Gas and water preflow	3 sec
Preheat (arc initiation by high frequency and upslope)	1.5 sec
Weld (starting with rotation and filler-metal feed)	2 min
Wire feed	1 min, 47 sec
Downslope	1 min, 55 sec
Gas and water postflow	10 sec

17 After three passes, water was circulated inside the pipes (if required) to keep the interpass temperature from exceeding 350 F. Interpass temperature was measured on the weld bead, using a calibrated contact pyrometer.
18 After each pass, the weld was checked visually for porosity, undercutting, cracks or poor appearance. Before the next pass was made, defects were removed by grinding with wheels that had been used only on 18-8 stainless steel.
19 The above procedures were repeated for the joint between pipes B and C.
20 After the welds were completed, weld metal was ground flush and inspected by the liquid-penetrant method. Welds, made in accordance with the ASME Boiler and Pressure Vessel Code, were inspected radiographically. The ASME Rules for Construction of Nuclear Vessels were also complied with.

Equipment cost for the operation amounted to about \$8000 — \$1000 for the lathe bed, which was purchased used, and about \$7000 for the welding machine, sequence timer, wire feed, electrode holder, cable, hoses, rotating drive, and the lathe modifications that were needed.

Root-Pass Welds Without Inserts. When the use of backing rings is prohibited, it is not essential to use consumable inserts to obtain smooth internal joint surfaces on pipe welds. An alternative method is to provide a groove weld with a root face of a width that permits complete root fusion in a single pass, using manual gas tungsten-arc welding and a gas backing. Filler metal is not used on the initial root pass. Subsequent passes to fill the joint may employ a different process, such as shielded metal-arc welding, because deposition of filler metal by manual gas tungsten-arc welding is relatively slow and expensive. An application of this type is described in the following example.

Example 244. Pipe Welding by Gas Tungsten-Arc Without Filler Metal for Root Pass, Shielded Metal-Arc for Filler Passes (Fig. 5)

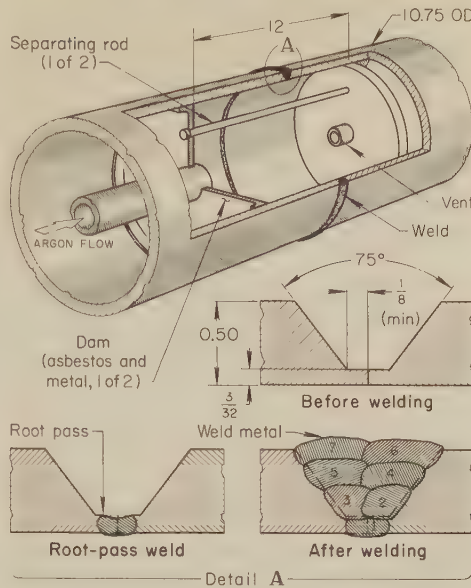
The 10-in., schedule 80S (0.50-in. wall) type 347 stainless steel pipe shown in Fig. 5 was used in oil-refinery equipment. Specifications called for pipe joints to have sound, complete-penetration welds conforming to the radiographic standards and other rules of the ASME code for unfired pressure vessels. The pipe joints also were required to have smooth, well-rounded inside surfaces; therefore, the use of solid backing strips was prohibited. Because there was no access to the inside of the joints, the success of the operation depended on the skillful execution of the root pass from the outside.

Manual gas tungsten-arc welding, with argon shielding and backing, and without the use of filler metal, was selected for the root pass. For the filler passes, shielded metal-arc welding was chosen.

Root-Pass Welding. Before welding, the pipe ends were beveled to the configuration shown in the "Before welding" view in Fig. 5. The joint area was cleaned of all oil, water and foreign matter. The pipe ends were then aligned, with root faces tightly butted, and tack welded.

The tack welded pipes were supported in position for welding, and purged with argon. This was accomplished by inserting two asbestos-and-metal dams as close to the joint as possible, and feeding argon through one dam and venting it (under back pressure) through the other, as shown in Fig. 5. After purging, a low flow of argon was maintained to provide backing during welding.

Type 347 base metal. Filler metals: none for root pass; filler passes, stainless steel (E347-16)



Root Pass (Gas Tungsten-Arc Welding)

Power supply	300-amp transformer-rectifier(a)
Electrode holder	200 amp, water cooled
Electrode	3/32-in.-diam EWTh-2
Filler metal	None(b)
Shielding gas	Argon, at 15 to 20 cfh
Backing gas	Argon, at 8 cfh
Welding position	Horizontal-fixed pipe
Arc length	1/8 in.
Current	70 amp, dcsp
Voltage	12 v

Filler Passes (Shielded Metal-Arc Welding)

Power supply	300-amp transformer-rectifier(a)
Electrode	E347-16 (1/8-in., first filler pass; 5/32-in., others)
Welding position	Horizontal-fixed pipe
Current (dcrp)	100 amp, first filler pass; 130 amp, others
Voltage	18 v, first filler pass; 20 v, others
Interpass temperature	350 F max

(a) With high-frequency generator, to facilitate arc starting. (b) In repair welding of root pass, 3/32-in.-diam ER347 welding rod was used.

Gas backing was used because the welded joint was required to have a smooth, well-rounded inner surface. Dams inserted in the pipe confined argon for purge backing and ensured minimum waste. Two-process welding, for which details are given in the table, resulted in 98% weld acceptability.

Fig. 5. Oil-refinery pipe with a circumferential butt weld for which root pass was made without filler metal (Example 244)

Conditions for welding the root pass are given in the table with Fig. 5. Welding was done in the horizontal fixed position, with the root pass being made in two semicircular halves beginning at the 6 o'clock position. The completed root-pass weld is shown in cross section in the lower left corner of Fig. 5.

In the horizontal fixed position, fusion of the root faces to form a uniformly smooth inside surface called for a high degree of welder skill, because the forces of gravity and surface tension acting on the molten weld puddle were in opposite directions at the top of the pipe and codirectional at the bottom — resulting in either convexity or concavity at the weld face. Thus, to ensure complete penetration, the welder had to avoid the formation of a large, superheated weld puddle by skillful control of heat input and welding speed.

Both visual and liquid-penetrant examinations were made on the completed root-pass weld, for defects such as cracks, porosity, excessive concavity or melt-through, and laminations. All defects were completely removed by grinding, and the defective areas were rewelded by the gas tungsten-arc process using ER347 filler metal. The repair welds were given visual and liquid-penetrant inspection, and if no further defects were found, the joint was cleaned and prepared for making the filler passes.

Filler-pass welding was done by the shielded metal-arc process, under the conditions given in the table with Fig. 5. Welding was done in the horizontal fixed position, using the same starting position and welding directions for each pass as in root-pass welding, but with a weaving technique. During the first filler pass, care was exercised to avoid burn-through of the relatively thin root-pass weld bead. After each of the six filler passes (see view at lower right in Fig. 5), slag was carefully removed by wire brush, or, if necessary, it was chipped out. Each pass was inspected visually for undercutting, slag inclusions, incomplete fusion, and porosity; areas with any of these defects were repaired by grinding and rewelding.

Interpass temperature, measured by a contact pyrometer, was maintained at 350 F max, but no preheat, postheat, or postweld heat treatment was used. The completed weld was inspected by either x-ray or gamma-ray radiography. Because of the care exercised in welding the root pass, defects averaged only 2% of the weld length.

Joint Design for Gas Tungsten-Arc Welding

Some typical joint designs for gas tungsten-arc welding of stainless steel, together with welding conditions for base metal in thicknesses ranging from 1/16 to 1/2 in., are given in Table 4. Joint designs reflecting actual industrial practice are illustrated in most of the examples in this article. Specific applications in which joint design was changed to obtain special advantages as a means of solving a problem in gas tungsten-arc welding are described in the next five examples.

Joint Design for Efficient Welding. In addition to its contribution to basic engineering requirements, joint design is a significant economic factor in welding, exerting a major influence on welding efficiency and cost. In production, some joint designs are difficult and time consuming to weld and, as discussed in the following example (also see Example 249), must be revised to conserve production time and labor.

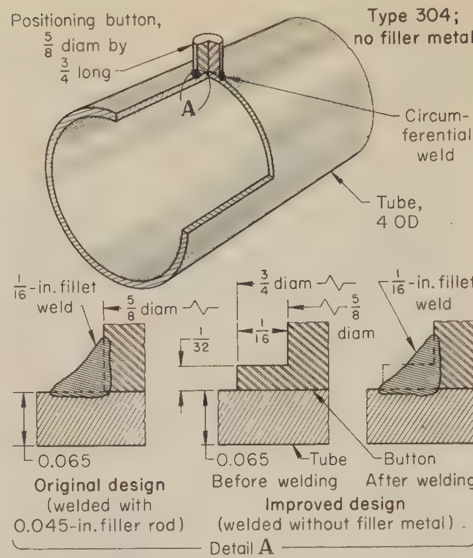
Example 245. Change in Joint Design That Eliminated Use of Filler Rod and Simplified Welding (Fig. 6)

Production of stainless steel molds for processing meat products required the welding of 19,600 positioning buttons to the surface of the mold tubes. The buttons, machined from type 304 bar stock, were ⅝ in. in diameter and ¾ in. long. The mold tubes, also of type 304, were 4 in. in outside diameter and had a 0.065-in. wall thickness. A portion of a meat processing mold with a positioning button welded to its surface is shown in Fig. 6.

The original joint design (see Fig. 6) called for placing the flat end of a button on the curved surface of the mold and depositing a 1⁄16-in. fillet weld around the base of the button, using manual gas tungsten-arc welding with a 0.045-in.-diam filler rod. A clamping fixture positioned the button and held it on the tube during welding. In a review of this procedure before production was started, it was apparent that the welder would have difficulty in maneuvering the electrode holder and filler rod around the button and also in maintaining a uniform fillet size.

The difficulty was avoided by changing the joint design so that the buttons could be welded to the mold surface without the use of filler metal. This was done by machining the buttons from ¾-in.-diam bar stock, so as to provide them with a shoulder, 1⁄16 in. wide and 1⁄32 in. thick, at the joint end. The ¾-in.-diam shoulder end of the button was welded, without filler metal, to the curved surface of the mold tube, with the shoulder forming a 1⁄16-in. circumferential fillet (see "Improved design" in Fig. 6). With the elimination of the filler rod, the welder had only the electrode holder to manipulate; as a result, welding speed was increased, control over penetration improved, and fillet size was more uniform. Welding conditions for the improved joint design are listed in the table accompanying Fig. 6.

The completed welds were wire brushed to remove any discoloration, and visually inspected for smoothness and uniformity of the fillet. Production rate averaged 38 buttons per hour. The improved welding speed and elimination of the filler rod more than offset the additional cost of machining the modified buttons.



Welding Conditions for Improved Design

Process	Manual gas tungsten-arc welding
Joint type	T, with shoulder
Weld type	Circumferential fillet
Fixtures	Clamping jig
Power supply	250-amp, three-phase transformer-rectifier
Electrode holder	300 amp, water cooled
Electrode	1⁄16-in.-diam EWTh-1
Filler metal	None (shoulder was fused)
Shielding gas	Argon, at 15 cfh
Welding position	Horizontal
Arc starting	Scratch
Arc length	⅛ in. (approx)
Current	34 amp, dcsp
Voltage	15 v
Welding speed	2 ipm (avg)
Production rate	38 buttons per hour

Fig. 6. Meat-processing mold with a positioning button that was redesigned for welding without filler metal (Example 245)

Joint Design for Structural Soundness. Joint design is sometimes modified to improve strength or rigidity, or to avoid a welding defect that would reduce structural soundness. In the following example, a visually attractive joint design was changed primarily to avoid burn-through.

Example 246. Redesign of Tube-to-Tube-Sheet Joint That Improved Weld Quality and Strength (Fig. 7)

Heat exchangers, designed for heating or cooling gases of various types, were made of parallel rows of oval-section type 304L stainless steel tubes seal-welded to a type 304L tube sheet, as shown in Fig. 7. Welds were made in a single pass by the manual gas tungsten-arc process, using argon shielding and ER308L filler rod.

In the original joint design (Fig. 7a), the tube sheet, 0.045 in. thick, was flared inward, and each seal weld was deposited between the rounded corner of the tube sheet and the 0.045-in. tube wall. The welds, although smooth and pleasing in appearance, were not of uniform quality, and many were structurally unsound. In attempting to obtain penetration to the point of tangency between tube and tube sheet, the welder sometimes burned through the tube sheet. Furthermore, with this joint design, the weld was in the area where high stress concentration was developed in service.

These shortcomings were overcome by changing to the improved joint design shown in Fig. 7(b). In this design, the thickness of the tube sheet was increased from 0.045 in. to 0.090 in., to provide more strength. The tube sheet was flared outward, making it possible for the welder to deposit a bead on the solid, exposed edges of the tube and tube sheet, and thereby to avoid burn-through. The improved joint resulted in welds being more uniform, and in weld repairs being reduced to a minimum. Conditions for manual gas tungsten-arc welding of the improved joint are given in the table with Fig. 7.

After welding, the joints were inspected visually for continuity, size and general quality. If required, the welds were liquid-penetrant inspected for cracks. Each welder was required to pass a qualification test as set forth in section IX of the ASME code on welding qualifications.

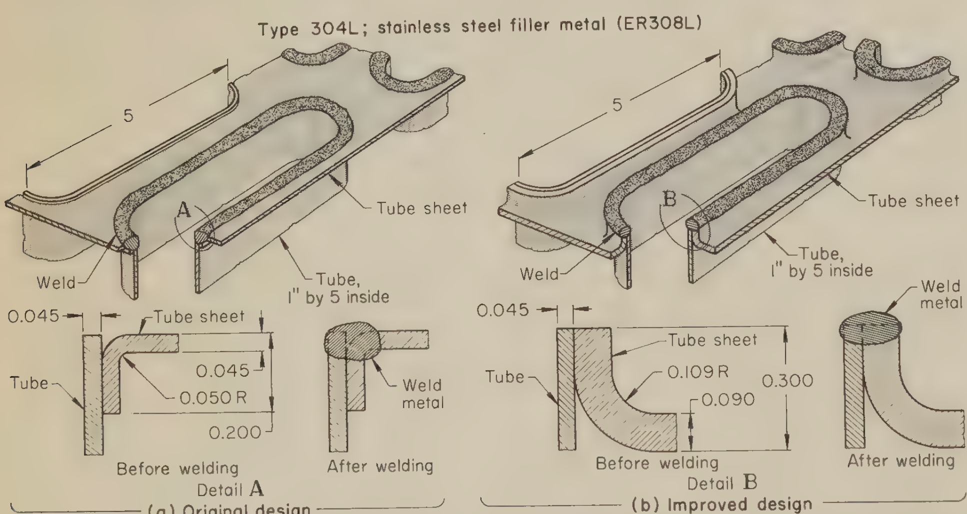
Heat exchangers were also fabricated from types 304, 316 and 316L, using the same basic welding procedures and appropriate filler metals.

Joint Design for Difficult-Access Welding. In addition to the more common problems of welding efficiency and structural soundness, joint design must occasionally cope with the problem of accessibility for welding. The following example demonstrates how this problem was solved in part by the use of a comparatively wide root opening in a butt joint through which access was obtained to weld another joint, and by subsequently welding the first joint with a consumable insert.

Example 247. Welding Inaccessible Butt Joints in an Aircraft Wing Assembly Through a 0.090-In. Root Opening in Opposing Butt Joints That Were Then Welded Using "Keyhole" Inserts (Fig. 8)

The view at upper left in Fig. 8 shows a portion of an aircraft wing assembly that consisted of a one-piece outboard spar and two brazed honeycomb panels, the inner and outer skins of which were butt welded to four projections on the spar. All components of the assembly were made of PH 15-7 Mo stainless steel.

Obtaining sound butt welds between the 0.040-in.-thick inner skins of the honeycomb panels and the corresponding projections on the spar presented a major welding problem, because of the inaccessibility of the joints. The problem was solved by designing the joints between the 0.050-in.-thick outer skins and spar projections with a root opening of 0.090 in., welding the



Welding Conditions for Improved Design

Process	Manual gas tungsten-arc welding
Joint type	Edge
Weld type	Corner flange
Fixtures	Fit-up and welding table
Preweld cleaning	Solvent; stainless wire brush
Power supply	300-amp, ac/dc with high frequency
Electrode holder	300 amp, water cooled
Electrode	3⁄32-in.-diam EWTh-2
Filler metal	3⁄32-in.-diam ER308L
Shielding gas	Argon, at 15 cfh
Welding position	Flat
Number of passes	One
Arc starting	High frequency
Current	80 to 100 amp, dcsp
Voltage	12 to 14 v
Welding speed	2 to 4 ipm (approx)

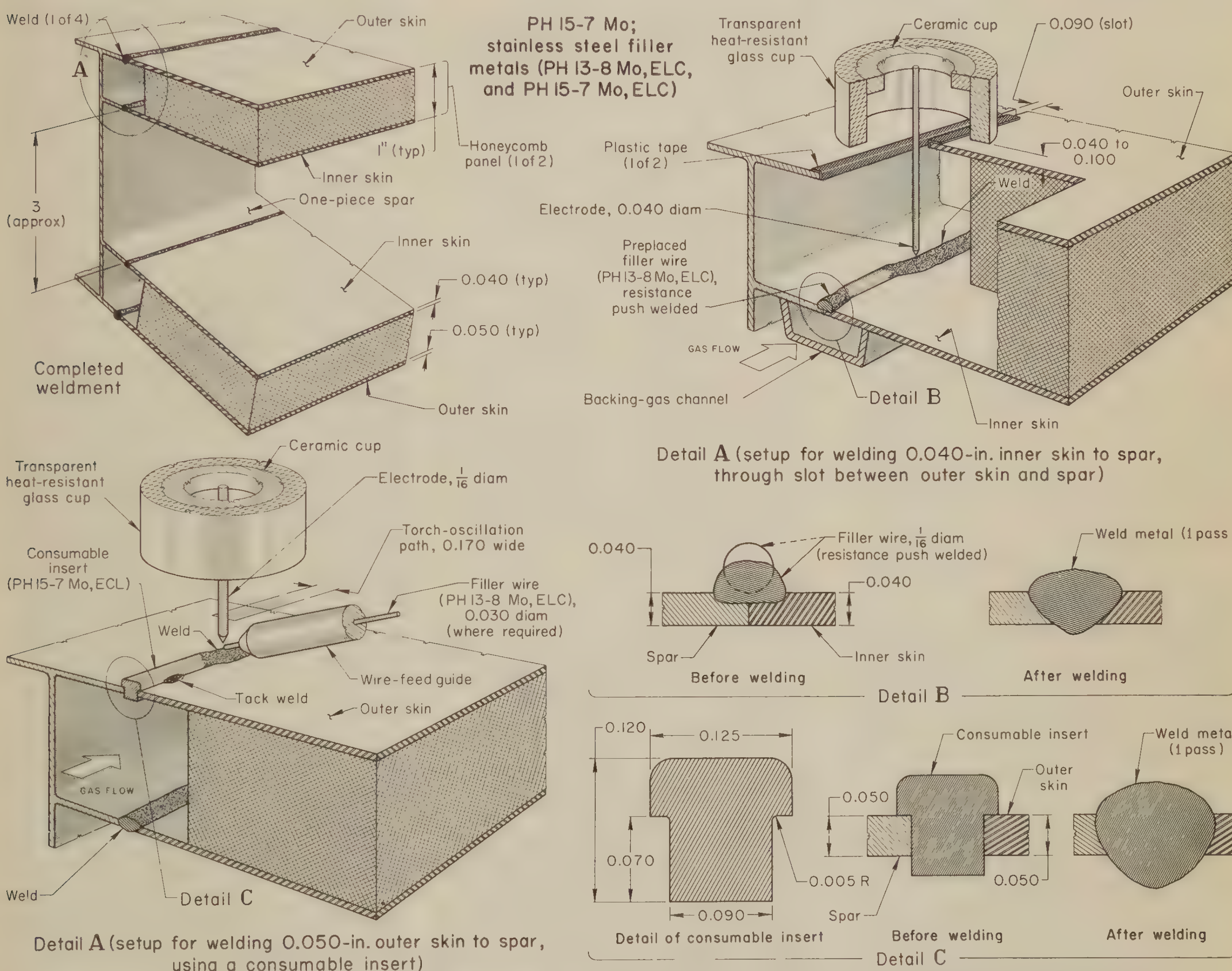
Fig. 7. Redesign of joint in a tube-to-tube-sheet weldment for a heat exchanger, which eliminated burn-through and resulted in stronger, more uniform welds (Example 246)

inner skins through this narrow (although wide for the base-metal thickness) slot, and then welding the outer-skin joints using "keyhole" consumable inserts. Despite the welding difficulties entailed, the design of the wing assembly was adopted because it minimized weight.

For welding each inner-skin joint, 1/16-in.-diam filler wire made of an extra-low-carbon PH 13-8 Mo stainless steel was preplaced along the centerline of the joint and resistance push (spot) welded at ¾-in. intervals to prevent it from being displaced during subsequent gas tungsten-arc welding (see "Before welding" in detail B in Fig. 8). Copper electrodes ¼ in. long and 0.070 in. in diameter were used for push welding, and the ground cable of the welding unit was attached to the spar.

Prior to automatic gas tungsten-arc welding of the inner-skin joint, plastic insulating tape was placed on the edges of the members separated by the 0.090-in. access slot, to prevent high-frequency arcing from the electrode to those edges. The joint was gas tungsten-arc welded using a 0.040-in.-diam thoriated tungsten electrode and welding-grade helium for shielding. The electrode holder was modified by bonding a transparent heat-resistant glass cup to the ceramic cup provided with the holder, to aid the operator in monitoring the position of the electrode with respect to the joint and the edges of the access slot. Argon was supplied to the underside of the weld through a backing channel. The welding setup is shown in detail A at upper right in Fig. 8. Welding conditions for the inner-skin joints are given in the table accompanying Fig. 8. After welding, the joint was radiographically inspected.

For welding the outer joint, a keyhole-section consumable insert formed from ⅛-in.-diam wire of an extra-low-carbon PH 15-7 Mo stainless steel was press fitted into



Welding condition	0.040-in. inner skin to spar	0.050-in. outer skin to spar
Process	Automatic gas tungsten-arc welding	Automatic gas tungsten-arc welding
Joint type	Butt	Butt
Weld type	Square groove, no root opening	Square groove, 0.090-in. root opening
Electrode holder	200 amp, water cooled	200 amp, water cooled
Electrode	0.040-in.-diam EWTh-2	1/16-in.-diam EWTh-2
Filler metal	1/16-in.-diam PH 13-8 Mo, ELC, wire(a)	PH 15-7 Mo, ELC, insert and 0.030-in.-diam PH 13-8 Mo, ELC, wire(b)
Shielding gas (at torch)	Helium, at 120 cfh(c)	Argon, at 24 cfh
Backing gas	Argon, at 35 cfh	Argon, at 40 cfh
Welding position	Flat	Flat
Arc starting	High frequency	High frequency
Arc length	0.020 in., start; 0.040 in., weld	0.050 in., approx
Current	26 to 30 amp, dcsp	65 to 70 amp, dcsp
Filler-metal feed rate	....	20 ipm
Torch oscillation	None	72 to 80 per min; 0.170-in. amplitude

(a) Wire was preplaced on the joint by resistance push welding. (b) Insert was press fitted into root opening of joint, and tack welded with ⅛-in. welds at ¾-in. intervals on alternate sides of joint. Filler wire supplied additional filler metal during welding. (c) High flow rate was needed to force adequate quantity of shielding gas through the 0.090-in.-wide slot.

Fig. 8. Aircraft-wing honeycomb-panel assembly in which joints between the one-piece spar and the inner and outer skins were welded by the two different methods shown (and detailed in the table), to overcome inaccessibility of the inner-skin joints (Example 247)

the 0.090-in. root opening (see detail C in Fig. 8). The insert was manual gas tungsten-arc tack welded with ⅛-in.-long welds placed alternately on each side at ¾-in. intervals. After the consumable insert had been tack welded, the joint was welded by the automatic gas tungsten-arc process, under the conditions in the table with Fig. 8, with argon shielding at the torch and argon backing supplied through the enclosure formed by the members. During welding, the torch was oscillated over a width of 0.170 in., and additional filler metal was added from the panel side. A typical setup used for welding is shown in detail A at lower left in Fig. 8.

The process was readily automated with the aid of high-precision welding equipment, including a welding head and wire-feed drive mounted on an air-driven or motor-driven carriage (not shown in Fig. 8) with provision for accurate torch positioning and torch oscillation, when required. The travel of the torch was precisely controlled by means of a drive wheel geared to a track held in position by vacuum-pumped cups.

Although the welding operations were difficult, defect-free welds were obtained when the proper welding procedures were carefully followed. In addition to maintaining fitup, two of the most important factors in achieving defect-free welds were proper joint cleaning prior to assembly and adequate shielding of the weld area by the inert gases during welding.

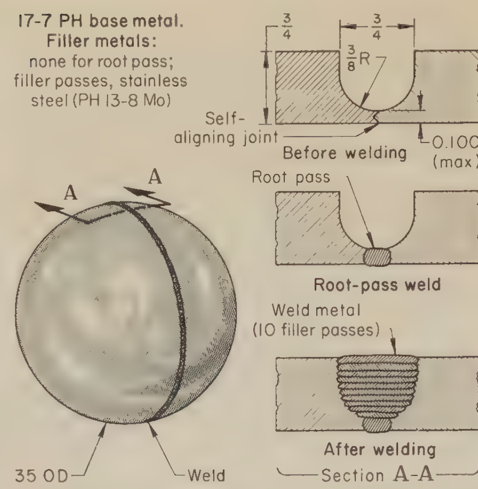
Joint Design for Alignment. When two components must be joined in accurate alignment, the use of fixtures to ensure alignment may not always be feasible or fully effective. In such applications, provision for proper alignment may be incorporated in the design of the weld joint, as illustrated by the next example.

Example 248. Self-Aligning Joint for Welded Hemispheres (Fig. 9)

Two hemispheres, 35-in. OD by ¾ in. thick, which were forged from 17-7 PH stainless steel, were welded by the automatic gas tungsten-arc process to produce a pressure vessel (Fig. 9) for containment of helium under high pressure. Selection of 17-7 PH stainless steel for the hemispheres was based on the resistance of the steel to corrosion and on the response of the steel to heat treatment after welding. To ensure self-alignment of the hemispheres and to avoid mismatch during welding, a specially designed joint containing a notch (Fig. 9, upper right) was used.

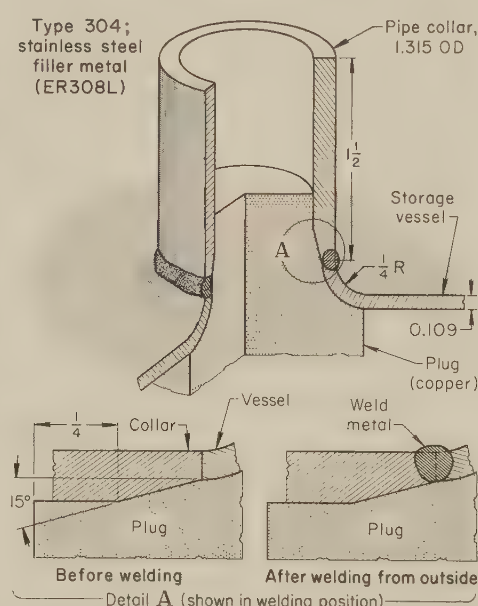
Equipment for welding included a special oscillating head with automatic arc-voltage control. The assembled hemispheres were rotated in a circumferential fixture mounted on turning rolls. Helium shielding was used at the arc, and free-flowing argon was fed to the interior of the sphere through a port (not shown in Fig. 9).

The root pass was made without the use of filler metal and without oscillation of the welding head. Ten subsequent passes were made with oscillation of the welding head, and with filler metal consisting of 0.045-in.-diam PH 13-8 Mo stainless steel wire continuously fed to the joint. The oscillating technique minimized the amount of interpass cleaning required, and also minimized the entrapment of inclusions.



Vessel was welded by the automatic gas tungsten-arc process, using an oscillating technique for the ten filler passes.

Fig. 9. Helium-storage vessel with a self-aligning joint (Example 248)



Welding Conditions for Outside of Joint(a)

Process	Manual gas tungsten-arc welding
Joint type	Circumferential butt
Weld type	Square groove
Fixture	Backing and alignment plug (copper)
Power supply	250-amp transformer-rectifier
Electrode holder	300 amp, water cooled
Electrode	$\frac{1}{16}$-in.-diam EWP(b)
Filler metal	$\frac{1}{16}$-in.-diam ER308L(c)
Shielding gas	Argon, at 15 cfh
Welding position	Horizontal-fixed pipe(d)
Number of passes	Two(a)
Arc starting	Scratch
Arc length	$\frac{1}{16}$ in.
Current	70 amp, dcsp
Voltage	14 v
Filler-metal feed rate	2.5 ipm
Welding speed	4 ipm

(a) After welding from the outside and removing the plug, an inside pass was made without filler metal, to ensure complete penetration. (b) Ground to a sharp point. (c) ER308L was used with type 304 base metal to minimize carbide precipitation. (d) Top half of weld was deposited, assembly was turned 180°, and weld was completed.

Butt-welded joint shown replaced a double-fillet-welded joint between unbeveled pipe collar and wall of an unflared hole in the top of the vessel, and consequently reduced welding and grinding time in addition to providing a radiused neck for easier cleaning.

Fig. 10. Setup and joint design for butt welding a pipe collar to a milk-storage vessel (Example 249)

Joint Design for Food-Processing Equipment. Stainless steel weldments are extensively used in the fabrication of equipment for food processing and for processing organic materials subject to microbial attack or deterioration through decomposition. In designing equipment of this type, emphasis is placed on the thoroughness with which it can be quickly cleaned and sterilized, and care is taken to ensure the absence of pits, sharp pockets or deep corners, where process materials can be entrapped. Smoothly polished, corrosion-resistant interiors with generously filleted corners and large transition radii are recommended, and are often prescribed by sanitary codes.

Manual gas tungsten-arc welding is frequently used for these weldments, because it provides good deposition control and clean welds, and varying contours can be followed with comparative ease. Wherever possible, butt welds are used in preference to fillet welds, because they are easier to grind and finish, and because they are less likely to have crevices that cannot be cleaned. Sometimes, a joint that would ordinarily be fillet welded can be changed to one employing a butt weld, with a resultant saving in cost, as in the following example.

Example 249. Change in Joint Design That Improved Weld Quality and Joint Function, and Reduced Cost (Fig. 10)

A type 304 stainless steel milk-storage vessel of 0.109-in. wall thickness required the attachment of a 1½-in. length of 1-in. schedule 80 (0.179-in. wall) type 304 stainless steel pipe, to serve as a collar for a measuring-stick opening.

Conventional installation of the collar comprised the following steps: (*a*) fitting the pipe in a hole in the flat top of the vessel, (*b*) tack welding the pipe in position, (*c*) depositing a fillet weld on the outer and inner edges of the joint, and (*d*) grinding and polishing the internal corners to the desired radius with a No. 4 finish. The fillet welds were deposited by manual gas tungsten-arc welding, using ER308L filler metal. The principal disadvantage of this procedure was the time and care required in grinding a smooth internal contour from the inside edge of the welded pipe. Too little grinding left undesirable rough spots; too much grinding removed the weld, necessitating repair welding and more grinding. In addition, weld shrinkage caused distortion of the thin wall of the vessel.

The difficulties were overcome by redesigning the joint as shown in Fig. 10. In the improved design, the opening at the top of the vessel was swaged to a flared neck with a flat top edge to which the pipe collar, now with a short length beveled on the inside to the 0.109-in. wall thickness of the vessel, was butt welded. Before welding, a solid copper plug, machined to fit the inside contour of the swaged neck and the beveled end of the collar, was inserted in the neck, and the beveled pipe was slipped onto the projecting plug for retention during welding. The joint was welded in a single pass by the manual gas tungsten-arc process, under the conditions given in the table with Fig. 10. After removal of the plug, the inside of the joint was given a fusion pass (no filler metal) to ensure complete penetration.

The improved joint design provided a smooth weld with a minimum of grinding, resulted in a reduction of welding and grinding costs, and avoided distortion of the relatively thin wall of the vessel. In addition, the radius of the swaged neck made the vessel easier to clean.

Cleaning and Preparation for Gas Tungsten-Arc Welding

In gas tungsten-arc welding of stainless steel, it is especially important that the weld area be clean and free of grease, oil, crayon markings and other foreign matter. Organic materials on the surface can break down in the heat of the arc and cause porosity or

carburization of the weld metal. Many inorganic contaminants, such as sulfur and sulfur compounds, are sources of corrosion and embrittlement.

Heavily soiled workpieces are usually cleaned by immersion in emulsion or solvent cleaners followed by vapor degreasing in a chlorinated solvent. During welding, fumes from chlorinated solvents break down in the heat of the arc and form a toxic gas. Therefore, when workpieces have been cleaned with such solvents, the welding area, as well as the cleaning area, must be properly ventilated to remove fumes and vapors. The cleaning and welding areas should be separated to ensure that fumes from the cleaning area do not reach the welding area.

Surface oxides are normally removed from stainless steel by acid pickling or, if present as a heavy scale, by mechanical cleaning operations such as wire brushing, grinding, and abrasive blasting. Wire brushing should be done with stainless steel brushes only, and these brushes should not be used on materials other than stainless steel. Similarly, grinding wheels and abrasives used on stainless steel should be used on these steels exclusively, to avoid contamination by inclusion of foreign materials.

One plant has reported the following methods to be most effective for cleaning and preparing stainless steel sheets prior to welding by the automatic gas tungsten-arc process:

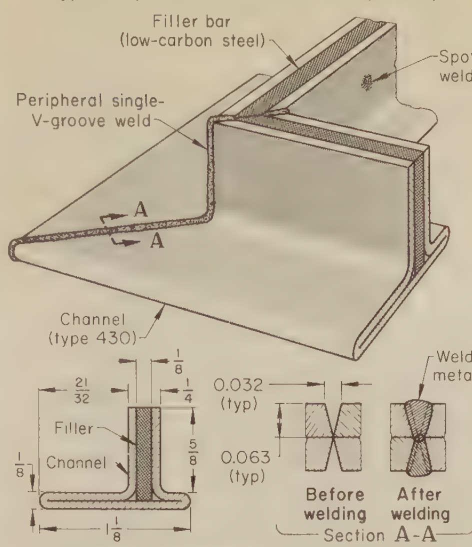
1 Sheets contaminated by grease or oil are degreased.
2 Edges to be joined are drawfiled to remove residues of dirt and grease smeared into the metal by shearing operations.
3 Sheets are sanded for a distance of ½ in. back from the edge of the joint to ensure removal of all surface oxides.
4 Loose residues from sanding and filing are removed by wiping the entire joint area several times with a cloth soaked in methyl ethyl ketone.
5 After the joint has been cleaned, extreme care is taken not to contaminate the joint area by touching it or dragging it across a dirty table. Operators are required to wear clean gloves.
6 Welding tools are wiped clean with a cloth soaked in methyl ethyl ketone.
7 When more than one hour elapses between the completion of cleaning and the beginning of welding, the joint area is wiped again with a cloth soaked in methyl ethyl ketone, immediately prior to welding.

Cleaning for Minimum Porosity. The relative cleanness of the weld area before welding will directly affect the amount of porosity that is found in the weld. Thus, when radiographic standards for allowable porosity are stringent, more than the usual amount of cleaning may be required to satisfy these standards, as described in the following example.

Example 250. Improvement in Cleaning Procedure That Reduced Porosity of Welds in PH 14-8 Mo Sheet to Radiographic Acceptability

A joint-cleaning procedure that was thought to be adequate proved otherwise when 50-in.-long butt joints between 0.052-in.-thick sheets of PH 14-8 Mo stainless steel were gas tungsten-arc welded. The sheets had been sheared to size, the joint edges and ½ in. of adjacent surfaces had been sanded, and the edges of the joint were detergent cleaned by wiping

Type 430; stainless steel filler metal (ER430)



Process	Manual gas tungsten-arc welding
Joint type	Butt and corner
Weld type	Peripheral single-V groove
Fixtures	Clamping jig and rotating positioner
Power supply	300-amp transformer-rectifier(a)
Electrode holder	200 amp, water cooled
Electrode	1/16-in.-diam EWTh-2
Filler metal	1/16-in.-diam ER430
Shielding gas	Argon, at 5 cfh
Welding position	Flat
Arc starting	Scratch
Current	31 amp, dcsp
Preheat and postheat	None

(a) With high frequency, upslope and downslope adjustment, and time delay for gas and water

Fig. 11. Corner of a door frame that was satisfactorily welded without preheat or postheat, because of rapid cooling provided by thinness of base metal and presence of a filler bar (Example 251)

with a cloth. After ten sheets had been welded, however, radiographic inspection showed that all welds contained pores larger than the maximum allowable size (0.008-in. diameter).

Close examination of the sheared edges of unwelded sheets showed that, despite the thinness of the sheets, shear-blade action had smeared over a portion of the edges. Oil and small particles of dirt that had not been removed by sanding and detergent cleaning were found lodged in tiny crevices. This condition was corrected by hand drawfiling the sheared edges prior to sanding and detergent cleaning. Three joints welded after the adoption of this improved method of edge preparation were well within the radiographic requirements for this application. To verify the results, sample welds were made between sheets that had been drawfiled and between sheets that had not. Radiographic inspection showed that only the welds joining the drawfiled sheets satisfied specification requirements. Of more than 100 production welds made using the revised joint-cleaning procedure, fewer than 5% were rejected because of porosity.

Preheating may be considered an essential step in the preparation of certain stainless steels for welding, notably the ferritic and martensitic alloys. The principal reason for preheating is to ensure that cracking does not occur in the weld or in the heat-affected zone. Recommendations for the preheating of ferritic and martensitic stainless steels are given in the two sections that begin on page 248 in this article, which deal specifically with the welding and metallurgical characteristics of these steels.

In the example that follows, preheating of a ferritic steel was not required, because of the thinness of the base metal (0.063 in.) and the rapid rate of cooling of the joint from the welding temperature.

Example 251. Welding Mitered Corners of Structural Frames Without Preheat or Postheat (Fig. 11)

Frames for glass doors were fabricated by joining the mitered corners of channel sections (Fig. 11) formed from type 430 stainless steel strip. Each channel section was reinforced with a ⅛-in.-thick low-carbon steel filler bar, which was spot welded to the inside of the channel.

The corners to be joined were mitered with a saw, and the edges were hand ground to a 1/64-in. bevel so that the abutting edges made a single-V groove 0.032 in. wide. Before welding, the edges of the joint were degreased with trichlorethylene. The frame sections were assembled in a clamping jig for proper alignment and mounted on a rotating positioner, and welded without preheat. Using manual gas tungsten-arc welding with argon shielding and ER430 filler metal, a continuous single-pass weld bead was deposited at the mitered joint under conditions listed in the table accompanying Fig. 11. To ensure that the continuous weld was deposited in the flat position, the positioner was capable of moving in both horizontal and vertical planes, as required. A frame was not removed from the positioner until welding was completed. At peak production, two positioners were used, permitting one assembly to cool in the positioner while a second assembly was being welded. After welding, the joints were cleaned on a belt sander to remove excess weld metal, and the inside and outside corners were trued by filing and grinding. The welded assembly was finally polished on a belt sander.

Although the channels were not preheated before welding, no cracks developed in either the weld metal or the heat-affected zone. The ability to deposit a relatively ductile and crack-free weld was attributed to the thinness (0.063 in.) of the channel and the mass of the filler bar — which caused rapid cooling of the joint from the welding temperature. Because of the extremely brief dwell time at the elevated temperature, grain coarsening and embrittlement were largely prevented. Consequently, postheating was not required, because the weld was both sufficiently ductile and corrosion resistant to satisfy the anticipated service conditions.

Automatic Gas Tungsten-Arc Welding

Gas tungsten-arc welding can be mechanized to assume some or all of the functions and controls performed by a welder. In general, the degree of mechanization is determined by the number of identical welds to be made, and by the speed and quality desired (see "Automatic Welding", which begins on page 133 in the article on Gas Tungsten Arc Welding).

Closure of Small-Diameter Tubes. Various types of stainless steel are used in the manufacture of small instrument components that embody a welded joint or closure. Accurate placement of small welds often demands machine-guided, rather than manual, welding, and a welding procedure that will not necessitate postweld cleaning and oxide removal is highly desirable. The gas tungsten-arc process is often selected when automatic welding is required, because it permits accurate, re-

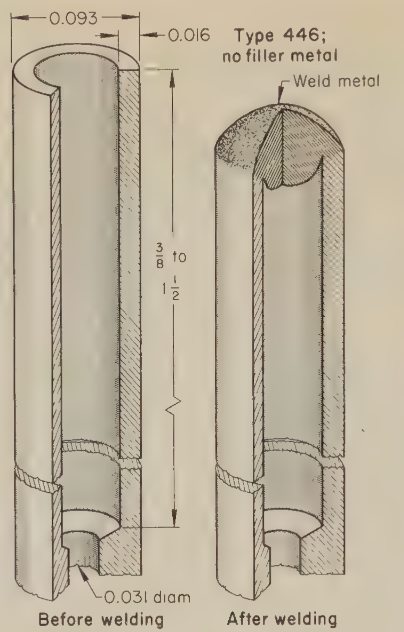
producible control of all welding conditions, together with a type of shielding that ensures a clean, oxide-free weld zone. When large quantities of delicate parts are required, high production rates can be obtained by employing suitable tooling, as described in the following example.

Example 252. Closing Ends of 1000 Temperature-Sensing Tubes per Hour by Automatic Welding Without Filler Metal (Fig. 12)

Figure 12 shows a 0.093-in.-OD type 446 stainless steel temperature-sensing tube that was bored at one end to increase the inside diameter from 0.031 to 0.061 in., for a depth of ⅜ to 1½ in. (depending on application). A leakproof seal at the bored end of the tube was obtained by automatic gas tungsten-arc welding without filler metal, under the conditions given in the table with Fig. 12.

Before being welded, the tubes were vapor degreased, and then freed from surface oxides by being heated at 1750 F in a conveyor furnace containing a hydrogen atmosphere. The tubes were then furnace cooled to room temperature and manually loaded into the ten holding chucks of a rotary indexing table. The chucks accurately positioned each tube under the electrode tip during welding.

The tubes were purged with argon immediately before welding, to prevent oxidation of the bore during welding. Preweld argon flow, weld time, and postweld argon flow were automatically controlled by a sequence timer. Using an arc time of 0.5 sec, the bored ends of the tubes were welded at the rate of 1000 per hour. After the tubes had cooled sufficiently (under argon), they were automatically ejected from the holding chucks. Quality control was maintained by visually inspecting the finished temperature-sensing tubes on a sampling basis. Rejection rate was less than 1%.



Automation	Rotary indexing table(a)
Power supply	200-amp transformer-rectifier
Electrode holder	Machine held, air cooled
Electrode	0.040-in.-diam EWTh-2(b)
Filler metal	None
Shielding gas	Argon, at 12 cfh(c)
Arc starting	High frequency
Arc length	0.030 in.
Current	60 amp, dcsp
Voltage	8 v
Weld time	0.5 sec
Production rate	1000 tubes per hour

(a) Equipped with ten workholding chucks, and automatic unloading mechanism; indexing speed, 3.6 sec per piece. (b) Ground to a pencil-point tip configuration. (c) Argon was also used for purging, immediately before welding.

Fig. 12. Temperature-sensing tube in which closure was produced at high speed by automatic gas tungsten-arc welding without filler metal (Example 252)

Welding of Sheet. Automatic gas tungsten-arc welding can be readily adapted to the welding of stainless steel sheet and products formed from sheet. It is widely used in the aircraft industry for this purpose because of its reliability and high joint efficiency. The following three examples illustrate joint designs and describe welding procedures used by a manufacturer of aircraft engines.

Examples 253 to 255. Production of Aircraft-Quality Butt Welds by Automatic Welding of Stainless Steel Sheet (Fig. 13)

Example 253. The joint design and workholding setup for butt welding two sheets of type 316 stainless steel sheet of slightly different thicknesses (0.093 and 0.095 in.) in a single pass are shown in the top view in Fig. 13. The 0.095-in.-thick sheet had been formed to the shape of a tank head, and the butt joint was circumferential. As shown in Fig. 13, the joint was of 90° single-V-groove design, with a 0.030-in. root face. The sheets were held down by steel hold-down bars and clamped by a steel hydraulic expander. During welding, argon was fed through a backing groove in a copper insert in the expander, and to a trailer shield (not shown in Fig. 13), designed to protect the weld zone from oxidation during cooling. Helium was fed to the torch to provide a hotter arc. Other welding conditions are listed in the table with Fig. 13.

Example 254. In this application, a linear, square-groove butt joint, between two 0.034-in.-thick type 321 stainless steel sheets, was welded in one pass, using ER347 filler metal. The welding setup, which included two nickel-plated copper hold-down bars, a nickel-plated copper chill bar with a backing groove, and a steel clamping fixture, is shown in the middle view in Fig. 13. Argon was used for shielding at the torch and for backing, and in a trailer shield (not shown in Fig. 13). Welding speed was only 5 in. per minute, but this low speed was justified by the high quality of the welds in an application in which welding speed was not a major criterion. Additional welding conditions are given in the table that accompanies Fig. 13.

Example 255. This application entailed welding in one pass of a square-groove butt joint between two 0.050-in.-thick type 347 stainless steel sheets, using ER347 filler metal. The welding setup, shown in the bottom view in Fig. 13, was nearly identical to that used in Example 254. As shown in the table accompanying Fig. 13, welding speed was only 4.5 in. per minute.

Gas Tungsten-Arc Spot Welding

Gas tungsten-arc spot welding is well suited to the welding of austenitic stainless steel, particularly in thicknesses of 0.020 to 0.090 in. Manual equipment and completely mechanized equipment are available. The essential components are a torch (usually equipped with a vented nozzle), a power supply, a tungsten electrode, a trigger switch, and a timing unit. In operation, the torch is placed against the work, the trigger is depressed, and a spot weld is made in a predetermined time. Ordinarily, filler metal is not used. Straight-polarity direct current is most commonly used.

Arc Starting. Because the electrode is usually recessed, and because arc length must be closely controlled, starting of the arc may pose a problem. Manual scratch starting is never used. The methods that are used are high-frequency starting, retract starting, and pilot-arc starting.

High-frequency starting is the method most commonly used, although it is unreliable below about 30 amp.

Retract starting consists in advancing the electrode to the work and then retracting it to establish an arc.

Pilot-arc starting makes use of a low-intensity arc to establish a high-intensity arc. The low-intensity arc is maintained from the tungsten electrode to an auxiliary electrode, usually the nozzle. It ionizes the shielding gas, thus facilitating arc starting.

Advantages Over Resistance Spot Welding. The main advantage of gas tungsten-arc spot welding over resistance spot welding is that welds can be made when only one side of the workpiece is accessible, whereas resistance welding necessitates access to both sides of the work. In addition, the thickness ratio of the pieces being joined is less important in gas tungsten-arc spot welding than in resistance spot welding. No special cleaning is necessary to obtain arc spot welds of good quality. On equal cross sections, shear strengths are equivalent to those obtained with resistance spot welds. The capital outlay required for gas tungsten-arc spot welding equipment is considerably less than that required for resistance spot welding equipment. This is particularly advantageous when short production runs are contemplated.

Gas Tungsten-Arc Welding of Tubing

Because of the wide variety of industrial and engineering uses of stainless steel tubing, tube welding has widespread application both in the manufacture of tubes and in the assembly of tubular components. Manual and automatic gas tungsten-arc processes are well suited to the welding of stainless steel tubing, especially when tube wall thickness does not exceed about ¼ in.

For wall thicknesses greater than ¼ in., gas tungsten-arc welding may be used to make the root pass and one or two subsequent passes; but, to reduce cost, the bulk of the weld metal is more likely to be deposited using a process that has a higher deposition rate, such as gas metal-arc welding.

Circumferential Welding. Several stainless steels, including types 304L, 321, 347 and AM-350, are widely used in high-reliability hydraulic systems, such as those installed in aircraft. Choice of tube fittings and connections for these systems is often difficult because of the exacting requirements imposed. Mechanical threaded connections have limited ability to seal and to maintain maximum reliability consistently. Welded joints may be unsatisfactory or incapable of meeting all requirements, depending on joint design and welding procedure. One specification requires that the weld penetration be 100%, that the strength of the weld at the

service temperature be equal to that of the tubing, and that the weld be capable of meeting all performance requirements, including repeated flexure at 35,000-psi stress levels.

Five designs of welded tube fittings for hydraulic systems are shown in Fig. 14. The straight butt weld (Fig. 14a) is seldom used for thin-wall hydraulic tubing, because fixturing is generally needed for control of alignment and because the tubing is unsupported in the annealed heat-affected zones adjacent to the weld. The "wedding band" design (Fig. 14b) constitutes a slight improvement over the butt weld; the band is completely fused during welding, but the heat-affected zones still are unsupported.

The two designs most widely used are the sleeve butt weld (Fig. 14c) and the sleeve double weld (Fig. 14d). In these designs, a loose tubular sleeve supports the ends of the tubes and also serves to provide weld metal. Either a single or a double weld can be used to complete the joint. With a single weld (Fig. 14c), the tube ends are butted together inside the sleeve (a root opening of 0.030 in. max can be tolerated), and the weld penetrates both the sleeve and tube to fuse the butt joint. Because the sleeve covers the butt joint, it is not possible visually to ensure that the weld will be deposited precisely over the butted ends; accordingly, reliance must be placed on the use of appropriate guide markings or of gaging fixtures.

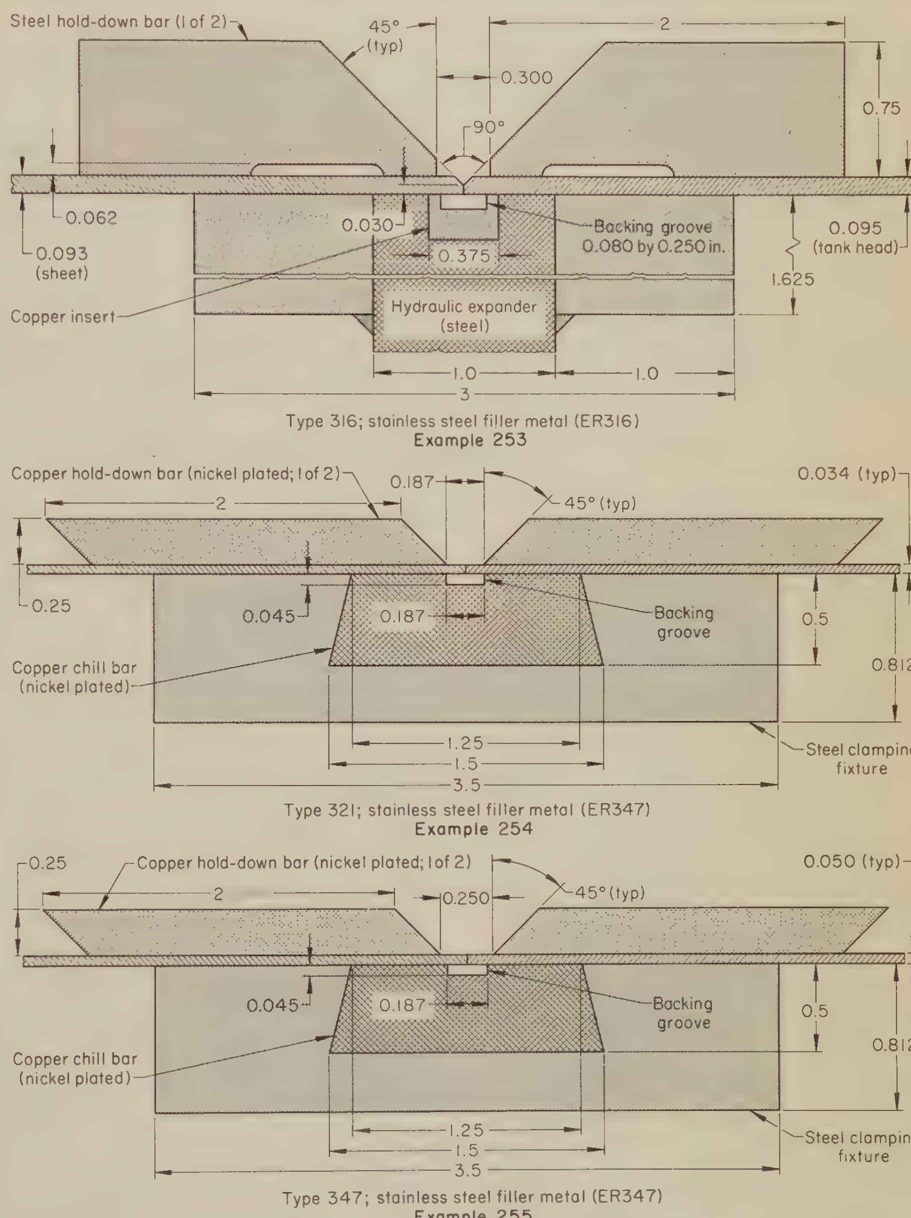
The use of a double weld on a tubular sleeve fitting (Fig. 14d), or of an expanded-tube lap weld (Fig. 14e), eliminates the need to butt the tube ends and makes location of the weld less critical. Nevertheless, it is still necessary to ensure that each weld joins the sleeve to the tube and that neither weld is made at the extreme end of a tube. These two designs place the weld in shear, and it is essential that the width of the weld be carefully controlled. Radiographic or ultrasonic inspection of the double-weld design (Fig. 14d) is difficult because of interference of the welds and tube ends.

The tubular sleeve designs, with either a single or a double weld, and the expanded-tube design support the tube in the heat-affected zones to the extent that the ultimate burst-pressure capability of the joint exceeds that of the system tubing. However, because of clearances, neither the tubular sleeve nor the expanded-tube design provides a snug fit to withstand vibration or flexing. Calculations indicate that the deflection required to take up the clearance exceeds the flex-endurance limit of the tube material.

This weakness can be largely overcome by swaging tubing and sleeve together. Other advantages of the swaged-on fitting over the loose-sleeve design are: (*a*) no clearance between sleeve and tube to entrap contaminants or corrodents, (*b*) no entrapment of air between sleeve and tube to cause contamination during welding, and (*c*) no need to purchase controlled-tolerance tubing or to size the ends of tubes before welding. A patented modification of the swaged-on design is discussed in the next example.

Example 256. Swaged-Sleeve Joint for On-Site Automatic Welding of Tubes for Aircraft Hydraulic Systems (Fig. 15)

Swaged-on 17-4 PH stainless steel sleeves with a mortise-and-tenon design, as shown in Fig. 15, were used in joining AM-350 stainless steel tubes for use in aircraft hydraulic systems. Swaging was performed on bench-type fixtures (to ensure precise positioning for swaging) before the tubes were installed in the aircraft. After swaging, the tube sections were installed in place and the mating ends positioned for welding; the interfitting axial projections on the sleeves provided exact radial location of the two ends to be joined. The assembly was then welded by the automatic gas tungsten-arc process without the use of filler metal. After welding, the coupling was a unitary structure, with the welded sleeve supporting the tube on both sides of the weld. The resulting joint provided the required resistance to vibration and flexing.



Welding condition(a)	Example 253	Example 254	Example 255
Electrode holder(b)	250 amp	250 amp	250 amp
Electrode(c)	$\frac{3}{32}$-in. EWTh-2	$\frac{1}{16}$-in. EWTh-2	$\frac{1}{16}$-in. EWTh-2
Filler metal(c)	$\frac{3}{64}$-in. ER316	$\frac{1}{32}$-in. ER347	$\frac{1}{32}$-in. ER347
Filler-metal feed, ipm	48.5	6	9
Shielding gas:			
At torch	Helium; 45 cfh	Argon; 30 cfh	Argon; 60 cfh
Backing	Argon; 30 cfh	Argon; 30 cfh	Argon; 80 cfh
Trailer shield	Argon; 20 cfh	Argon; 30 cfh	Argon; 60 cfh
Current (dcsp), amp(d)	105	40	73
Voltage, v	15	8	7.5
Welding speed, ipm	12.75	5	4.5

(a) For all three welds, joint preparation consisted of either machining or drawfiling the joint edge, followed by cleaning with silicon carbide abrasive and wiping with a solvent. (b) Water-cooled type. (c) Size given is diameter. (d) Power supply for all three welds was a 300-amp transformer-rectifier.

Fig. 13. Cross sections of three sheet-to-sheet butt joints, showing holding setups for single-pass automatic gas tungsten-arc welding to aircraft quality, under conditions given in table (Examples 253 to 255)

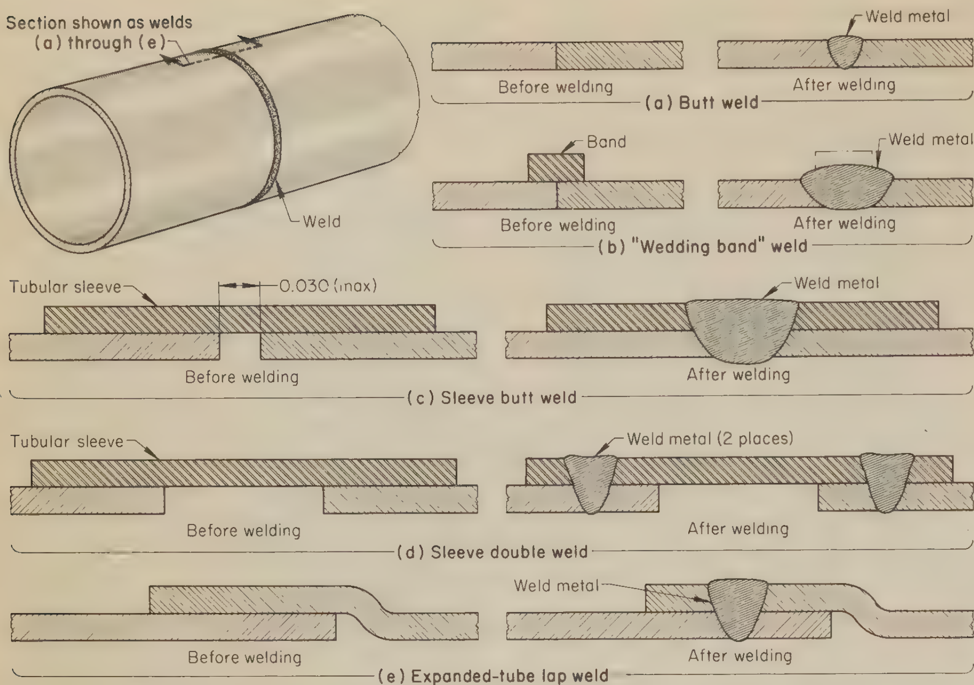


Fig. 14. Five designs of welded tube fittings for aircraft hydraulic systems

Equipment for welding consisted of a self-propelled orbital welding head with a split-ring clamping device designed to fit tightly over the sleeves, and a segmented gear (driven by a high-torque motor) from which the electrode was suspended; the gear served to rotate the electrode around the coupling joint. The orbital welding head was also equipped to supply shielding gas around the joint during welding. The power supply, a 300-amp transformer-rectifier, had built-in sequence controls for complete programing of the welding cycle.

Before welding, the inside of the tube was purged with argon, and a flow of argon was also maintained for backing. The welding head was clamped in position around the sleeve, the programer was set, and welding started. The programer automatically controlled the entire welding operation, including argon preflow, arc initiation (by high frequency), welding speed, current control, and arc termination. Welding conditions are given in the table accompanying Fig. 15.

Complete joint penetration was achieved, and the welds were easily subjected to radiographic and ultrasonic examination. Mechanical tests showed that the swaged-sleeve design outperformed other types of tubular sleeve design in resistance to high pressure and severe vibration.

Longitudinal Welding. The automatic gas tungsten-arc process is used for making longitudinal seam welds in structural tubing formed from thin stainless steel sheet. Welding can be done with or without filler metal. To obtain a high production rate, as in the application described in the following example, requires accurate forming of the tube section, close tolerances on fixturing and torch travel, and an efficient heat sink.

Example 257. High-Speed Seam Welding of Tubular Furniture Legs (Fig. 16)

Rectangular tubes, 6¹⁄₃₂ in. long, were formed from 0.024-in.-thick type 430 stainless steel sheet and seam welded for use as furniture legs (Fig. 16). To obtain high production rates, an automatic welding procedure, using the gas tungsten-arc process, was developed to weld the seam in a single pass without filler metal, at a speed of 60 in. per minute.

The operating sequence consisted in manually slipping the preformed tube over a copper backing die, clamping the tube in position, initiating the welding sequence, and, after welding, ejecting the part from the backing die automatically. Precise mechanical alignment throughout the welding operation was essential to ensure that maximum deviation of the arc from the seam did not exceed ±0.010 in. Forming of the tube also required a high degree of precision, because the fixture used during welding was designed only to hold the part, not to help form it.

The copper backing die served as a heat sink and as a support for fixturing; it was also provided with starting and ending tabs to avoid unstable arc initiation and decay. When the preformed leg had been properly positioned on the backing, a clamping fixture tightened automatically to hold the seam in close alignment.

A sequence timer incorporated with the power supply was preset for argon preflow, current-upslope control, and torch travel. The welding sequence was initiated by pushbutton, and by the time the electrode had traversed the starting tab, arc stability was established. Welding was done in the flat position. At the end of the welding cycle, a limit switch tripped the circuit, ending the operation with sequential current downslope, argon postflow, and travel stop. Argon backing was not used, because the appearance of the inside surface of the weld was not important to the application. Because type 430 steel is ferromagnetic, the nozzle of the electrode holder was equipped with a magnetic ring to prevent arc blow. Welding conditions for the application are given in the table accompanying Fig. 16. Approximately 100 of the tubular furniture legs were welded per hour.

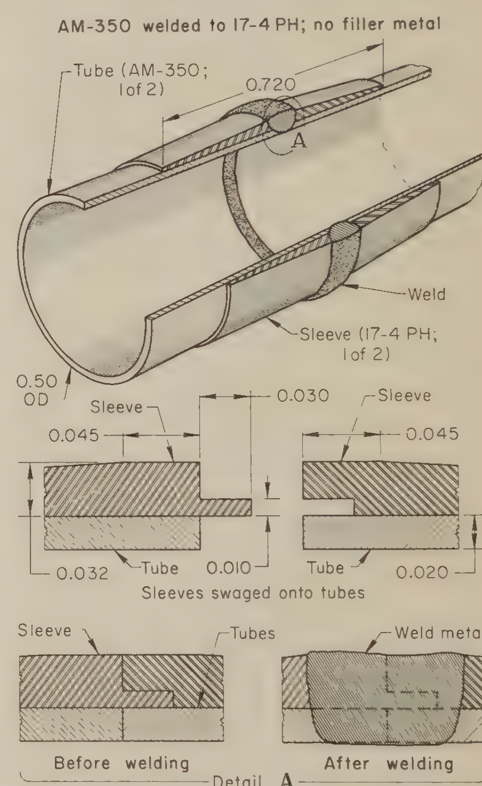
Welding of Tubes to Tube Sheet. Gas tungsten-arc welding is used in joining many types of assemblies that embody stainless steel tubular components. A typical application is the joining of tubes to tube sheets used in high-pressure heat exchangers. Various joint designs and weld configurations, and manual and automatic procedures for producing these critical welds, have been developed. (See Example 246, page 256, which describes an application in which redesign of the joint between tube and tube sheet resulted in improved weld quality and strength.)

Much of this type of assembly welding is done manually, especially on small installations, although automatic equipment has been developed for high production. Manual welding requires accurate control over torch movement, because the tubes used for these weldments have thin walls and usually are of small diameter.

The simplest joint design consists of a tube inserted in a straight drilled and reamed tube hole having no special weld-groove preparation and requiring no filler-metal addition, as described in the following example.

Example 258. Manual Seal Welding of Tubes to Tube Sheet, Without Filler Metal (Fig. 17)

Heat exchangers for use with corrosive gases contained 110 tubes (¾-in. OD, 0.049-in. wall) that were seal welded in a 1⅛-in.-thick tube sheet, as shown in Fig. 17. The tubes and tube sheet were made of



Process	Automatic gas tungsten-arc welding
Joint type	Butt(a)
Weld type	Offset groove
Automation	Self-propelled welding head(b)
Power supply	300-amp transformer-rectifier(c)
Electrode holder	Incorporated in welding head
Electrode	¹⁄₁₆-in.-diam, taper ground
Filler metal	None
Shielding gas:	
At torch	75% helium – 25% argon, at 20 cfh
Purging and backing	Argon, at 10 cfh
Welding position	All positions
Arc starting	High frequency
Arc length	0.050 in.
Current	14 amp
Voltage	16 v
Welding speed	5 ipm

(a) Sleeve with mortise-and-tenon joint aligned and fitted over tube. (b) With split-ring device for clamping the sleeve. (c) With controls for programing of weld cycle.

Fig. 15. Use of interlocking swaged-on sleeves (U. S. Patent 3,439,941) for high-reliability on-site welding of tube joints for aircraft hydraulic systems
(Example 256)

type 316L stainless steel and were designed for a maximum working tube pressure of 300 psi at 800 F. The tube-to-tube-sheet joints were welded by the manual gas tungsten-arc process in accordance with the requirements of the ASME code for unfired pressure vessels.

Before welding, the tubes and tube sheet were deburred and cleaned with carbon tetrachloride, using suitable precautions. No special edge preparation was required. The tubes were inserted in the 0.757-in.-diam holes in the tube sheet so that the ends of the tubes were flush with the tube-sheet face. The tubes were lightly expanded for a depth of 1 in. to hold them in place (see Fig. 17), and each was welded in a single pass without filler metal. Welding conditions for the operation are given in the table with Fig. 17.

After welding, tubes were re-expanded for a distance of ¾ in., starting ¼ in. below the welded joint. After assembly in the heat-exchanger shell, the tube bundle was subjected to a 600-psi hydrostatic test. Rejections because of tube-weld leakage averaged less than 0.01%.

Gas Tungsten-Arc Welding of Thin Sections

The welding of thin sections of stainless steel requires the use of low arc currents. The gas tungsten-arc process, widely used for joining thin sections, is generally satisfactory for welding at currents down to about 10 amp. Below this level, considerably more skill is required when welding manually, because a small change in torch standoff and arc length produces a change in arc voltage and results in a fairly large change in current. Therefore, to prevent significant fluctuation in arc current, automatic welding may be mandatory.

The welding of stainless steel in foil thicknesses can be simplified by converting a butt joint into some type of edge joint. Such a joint is easier to weld because it permits the widest latitude in fixturing tolerance and in welding conditions. The following example describes the application of automatic gas tungsten-arc welding to produce a leakproof joint between a diaphragm and backplate fitted to close dimensional tolerances.

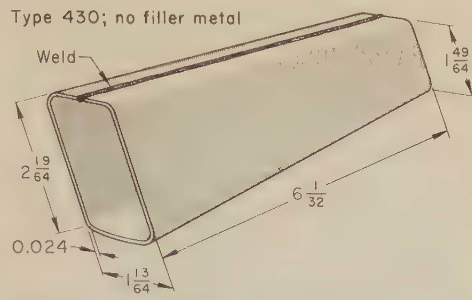
Example 259. Automatic Welding of a 0.002-In.-Thick 17-7 PH Diaphragm to a Type 316L Backplate, To Produce Leakproof Joints (Fig. 18)

The 0.7500-in.-diam diaphragm-and-backplate weldment shown in Fig. 18 was part of a pressure-control system used in ammonia refrigeration. Specifications required the joint between the edge of the 0.002-in.-thick diaphragm (17-7 PH) and the 0.010-in.-thick peripheral lip of the backplate (type 316L) to be leakproof at an air pressure of 650 psi under water. Attempts to join the components by epoxy bonding with a pressure ring and by brazing with silver alloy filler metal resulted in high rejection rates because of leakage; a successful joining procedure was developed, using automatic gas tungsten-arc welding under the conditions given in the table with Fig. 18.

The success of this procedure depended on matching the joint edges of the diaphragm and backplate within a tolerance of ±0.0002 in. on the diameter after assembly (see "Before welding" in detail A in Fig. 18). This was accomplished by carefully machining the baseplate and by forming the diaphragm in a die to close dimensional tolerances. The assembled components, with joint faces precisely aligned, were clamped between special holding fixtures attached to the headstock and tailstock of a small bench lathe. Accurate alignment of the parts was ensured during welding, to avoid arc deflection, and care was taken to prevent fluctuations in the power supply.

The welded assemblies were installed on the pressure-control system and tested for leakage at an air pressure of 650 psi, and a final halogen leak test was performed on a sampling basis, using a mixture of Freon and air at a pressure of 300 psi and a halogen leak-detector probe.

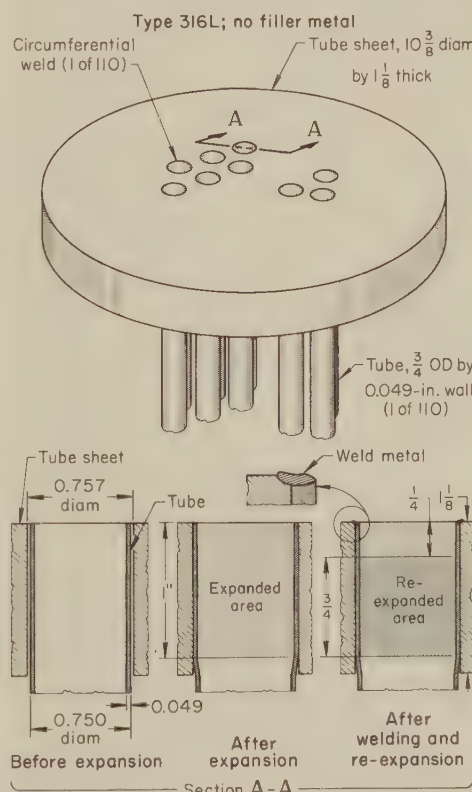
Thin-wall flexible stainless steel hose designed for pressure service must be equipped with reliable joints attaching nozzles or pipes. Depending on the severity of service, brazed joints and even mechanical joints may prove satisfactory, but in more critical applications, where the strength and corrosion resistance of the joint must be equivalent to those of the stainless steel hose, welded joints are usually more reliable. Control of heat input in welding the thin walls of the flexible hose is often difficult. In the welding of type 321 flexible hose to low-carbon steel pipe described in the next example, heat control was achieved by skillful use of manual gas tungsten-arc welding.



Process	Automatic gas tungsten-arc welding
Joint type	Butt
Weld type	Square groove
Fixtures	Copper backing die(a); holding clamps
Power supply	120-amp transformer-rectifier(b)
Electrode holder	150 amp, water cooled(c)
Electrode	3⁄32-in.-diam EWTh-2
Filler metal	None
Shielding gas	Argon, at 25 cfh
Welding position	Flat
Arc starting	On end tab of backing die
Arc length	3⁄32 in.
Current	80 amp, dcsp
Welding speed	60 ipm
Production rate	100 legs per hour

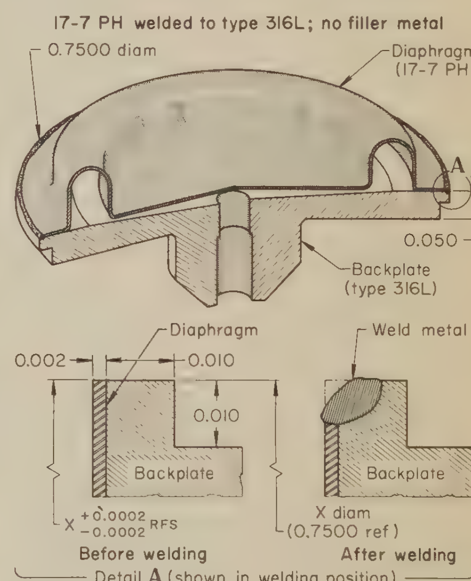
(a) Backing die had end tabs for starting and stopping. (b) With slope control and sequence timer. (c) Equipped with a magnetic ring at the nozzle.

Fig. 16. Furniture leg with a longitudinal seam that was automatically welded at a high production rate (Example 257)



Process	Manual gas tungsten-arc welding
Joint type	Square edge
Weld type	Seal
Power supply	400-amp motor-generator
Electrode holder	300 amp, water cooled
Electrode	1⁄16-in.-diam EWP
Filler metal	None
Shielding gas	Argon, at 20 cfh
Welding position	Flat
Arc starting	High frequency
Arc length	3⁄16 in. (approx)
Current	78 amp, dcsp

Fig. 17. Tube-to-tube-sheet weldment with simple joints that were manually single-pass welded without filler metal (Example 258)



Process	Automatic gas tungsten-arc welding
Joint type	Edge
Weld type	Seal
Fixtures	Holding clamps(a)
Power supply	300-amp transformer-rectifier(b)
Electrode holder	Air cooled(c)
Electrode	0.060-in.-diam EWP(d)
Filler metal	None
Shielding gas	Argon, at 15 cfh
Welding position	Horizontal-rolled pipe(e)
Number of passes	Two(f)
Arc starting	High frequency (with upslope control)
Current	30 amp (maximum)
Voltage	7 v
Welding speed	7 ipm
Welding time per assembly	1 min

(a) Attached to headstock and tailstock of a small bench lathe. (b) With upslope and downslope control; if available, a machine with smaller capacity could have been used. (c) Electrode fixed on movable arm. (d) Tapered to 0.010-in. diameter. (e) Work rotated at 3 rpm. (f) One revolution for preheat; then two welding passes.

Fig. 18. Weldment consisting of a foil-thin diaphragm and a backplate, which required accurate fitting and alignment to produce a leakproof edge joint (Example 259)

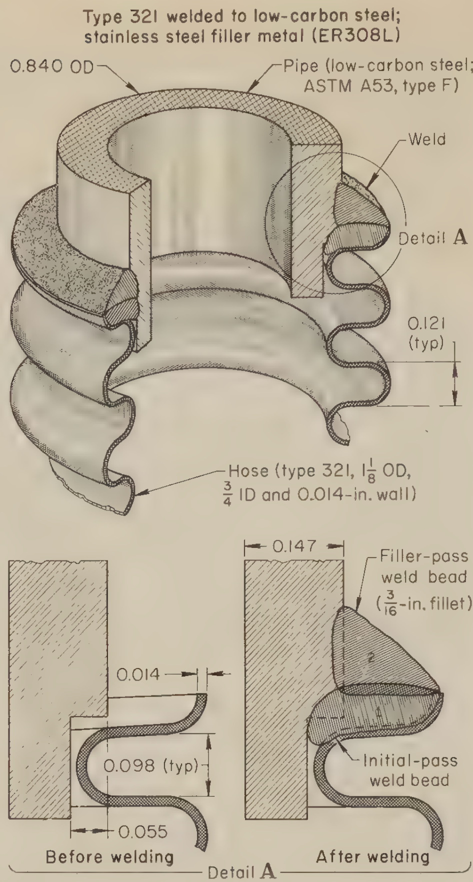
Example 260. Welding 0.014-In.-Wall Type 321 Flexible Hose to Low-Carbon Steel Pipe (Fig. 19)

The 0.014-in.-wall type 321 stainless steel flexible hose shown in Fig. 19 was used to carry ammonia coolant through oil filter-coolers for refrigerant compressors. The helically convoluted hose was bent in the shape of a coil, approximately 65 in. long, and the two ends of the hose were joined to recessed ends of ½-in. schedule 80 (0.840-in. OD) low-carbon steel (ASTM A53, type F) pipes at inlet and outlet terminals. The joints were designed to withstand a pressure of 150 psig in the temperature range of −20 to 200 F and were required to conform to the requirements of the ASME code for unfired pressure vessels.

In developing a welding procedure for the hose-and-pipe joints, silver brazing was tried initially, but was rejected because the ammonia reacted with the brazing filler metal; moreover, the strength of the joint was too low. Oxyacetylene welding, using a nickel filler metal, produced acceptable joints, but the filler metal was expensive and difficult to obtain, and the process resulted in excessive heating of the thin hose wall. Best results were obtained by manual gas tungsten-arc welding with ER308L filler metal, using a special technique to avoid burn-through.

Before welding, the ends of the hose and pipe were cleaned with emery cloth or stainless steel wool. The hose was cut and fitted to the end of the pipe as shown at lower left in Fig. 19, and the assembly was clamped together. To avoid burn-through of the thin hose wall, the joint was welded in two passes — an initial pass and a filler pass (for fillet-weld reinforcement). In the first pass, which was made at a low amperage (see table with Fig. 19 for welding conditions), weld metal was deposited on the flare of the hose wall and partly filled the groove between the hose and pipe (see view at lower right in Fig. 19). The second pass was made at a higher amperage to penetrate the first bead slightly, with the arc directed into the low-carbon steel pipe, to avoid excessive heating of the tube.

After welding, the joints were wire brushed to remove scale, and were pressure tested under water using nitrogen at 225 psig. About 95% of the joints were leakproof in the pressure test.



Process	Manual gas tungsten-arc welding
Joint type	Lap
Weld type	Groove and fillet
Power supply	300-amp transformer-rectifier
Electrode holder	130 amp, air cooled
Electrode	1/16-in.-diam EWTh-2
Filler metal	1/16-in.-diam ER308L
Shielding gas	Argon, at 10 cfh
Welding position	Horizontal (vertical pipe)
Number of passes	Two
Arc starting	Scratch
Arc length	⅛ in. (approx)
Current (dcsp) and voltage:	
First pass	10 amp; 15 volts
Second pass	55 amp; 9 volts
Preheat and postheat	None
Weld time	3 min per pass (approx)
Production rate (avg)	10 joints per hour

Fig. 19. Assembly of a thin-wall type 321 flexible hose and low-carbon steel pipe that was welded in a special two-pass sequence to avoid burn-through (Example 260)

Thin-Skin Missile Bodies. Some of the tubular body segments used in missile applications are made of stainless steel sheet that is only 0.028 in. thick; these cylindrical segments require both longitudinal and circumferential welds for assembly. Weld-quality requirements are unusually high and dimensional tolerances are stringent; this necessitates special care in shearing, cleaning, fit-up and welding, as described in the following example.

Example 261. Welding of Segments of Thin-Skin Missile Bodies (Fig. 20)

Cylindrical missile bodies were assembled by joining prefabricated segments of varying length. Each segment consisted of an outer skin, made up of longitudinally welded cylinders, and internal support frames, which were joined to abutting cylinders by circumferential welds that also joined the cylinders. A typical segment, 40 in. long, is shown at upper left in Fig. 20.

The outer-skin cylinders were roll formed from 0.028-in.-thick type 301 stainless steel blanks, sheared accurately to a width of 28.236 in. +0.002, −0.000 in.; length was also closely controlled.

The support frames were rubber-diaphragm formed from 0.032-in.-thick AM-350 stainless steel sheet, to a web width of 1½ in. and a flange width of ¾ in.; they had an outside diameter 0.050 in. less than the inside diameter of the outer-skin cylinder. After forming, the frames were rolled to produce a convex radius at the circumference, with the outermost diameter exactly matching the inside diameter of the outer-skin cylinder. A cross section of the frame before and after rolling is shown at lower left in Fig. 20.

Before welding, the cylinders and frames were cleaned and prepared as follows:

1. Clean in a hot (180 to 200 F) aqueous solution of heavy-duty alkaline cleaner (8 to 12 oz per gal) for 15 to 20 min.
2. Rinse in clean water at room temperature.
3. Descale in an aqueous solution of nitric acid (15 to 20%) and hydrofluoric acid (3 to 5%) at 120 to 140 F for not more than 30 min.
4. Rinse in clean water at room temperature.
5. Drawfile and deburr faying surfaces.
6. Wipe all surfaces with acetone, and remove residues with a lint-free cloth.

The upper right view in Fig. 20 shows the setup used for welding the longitudinal seam of each outer-skin cylinder. Conventional hold-down bars (not shown in Fig. 20) with 1-in.-wide fingers were used to clamp the cylinder at a pressure of 80 psi. The inner surface of the cylinder was supported by a deoxidized copper backing bar, which also served as a chill. Except for occasional repair welds, the longitudinal joints were welded without filler metal, because filler metal increased shrinkage and was not required to ensure x-ray soundness. Helium was used as backup and shielding gas. Starting and runoff tabs were used at the beginning and ends of the weld. Welding details for the longitudinal weld are given in the table with Fig. 20.

After fabrication of the outer skin, the supporting frames were fitted inside the cylinders (supported on a wooden block to prevent "belling" of the cylinder walls) at a distance of 8 in. from the ends as shown in Fig. 20 (upper left). The frames were joined to the outer skin of the cylinders by a single-pass circumferential melt-through weld. The frames provided backup for welding, and two copper rings (⅛ in. thick by 1½ in. wide) slipped over the cylinder served as hold-downs (see Fig. 20, detail B). This arrangement prevented any drawstring effect at the circumferential joint. Welding conditions for the circumferential joint are given in the table with Fig. 20. For joining the ends of two cylinders to a supporting frame providing internal linkage at the joint, an ER308 filler metal was used; other welding conditions were the same as those listed under "Circumferential weld" in the table.

Restricting the Heat of Welding. Small electrical assemblies are often protected by enclosure in sheet-metal housings which may be sealed mechanically or by soldering, brazing or welding, depending on the specific application and on cost considerations. The metal selected for the housing, as well as the method for sealing, usually depends on service requirements. When a small, delicate electrical switch assembly is enclosed in a stainless steel housing sealed by welding, extreme care must be taken to keep the assembled components clean, dry and relatively cool. Heat from welding must be minimized. Ordinarily, only automatic welding can provide the degree of control required to minimize the heat input and produce a smooth, leakproof joint, as illustrated in the following example.

Example 262. Automatic Precision Welding of Microswitch Housing Assembly With Minimum Heat Transfer to Internal Components (Fig. 21)

Enclosures for protection of microswitch assemblies, as shown in Fig. 21, consisted of 0.010-in.-thick (type 347) rectangular housings (with rounded corners) welded on one side to a 0.030-in.-thick (type 305) cover and hermetically sealed on the other (after backfilling with nitrogen) with a 0.1-in.-thick layer of dielectric material.

Welding of the recessed corner joint between the cover and housing (Fig. 21, detail A, Before welding) was accomplished in a single pass by the automatic gas tungsten-arc process with argon shielding (and backing) and without addition of filler metal. The welded joint was required to be leakproof with the leakage rate for each switch (after sealing) not exceeding 0.3 cu cm per year. Extreme care was required to minimize heat input during welding, in order to prevent damage to the brazed flexible diaphragm (Fig. 21) and other delicate components of the microswitch.

Several modifications in the process were adopted to minimize heat input. Thus, the tungsten electrode was taper ground to a point to obtain a fine, high-current-density arc at low amperage. Straight polarity was selected over reverse polarity to produce a finer arc and to avoid overheating the electrode tip. The combined effect of these modifications was to increase welding speed while limiting heat input to a narrow weld and heat-affected zone. Argon was selected over helium for shielding to obtain smoother arc action at lower voltage. Other advan-

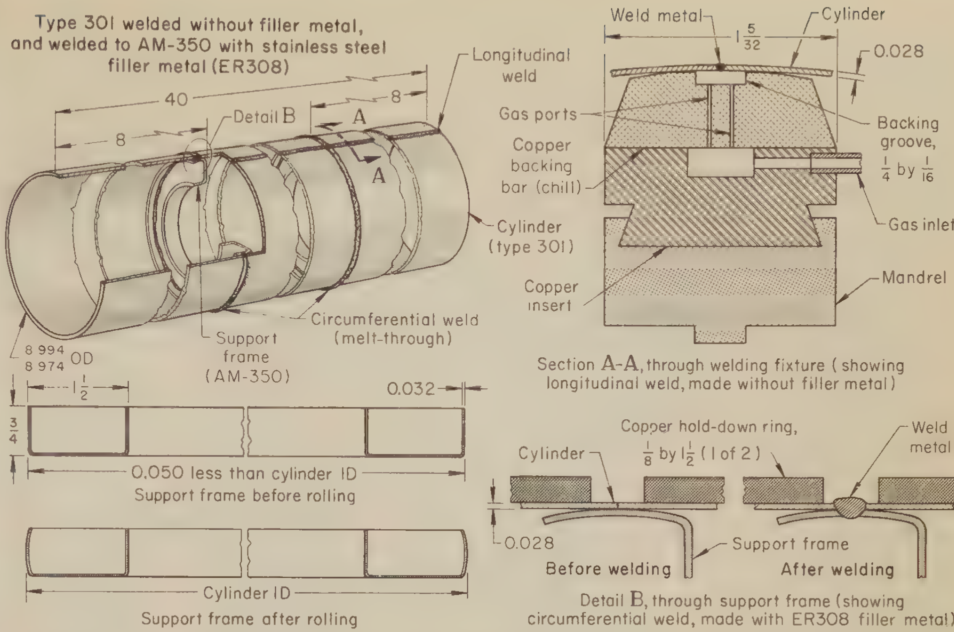
tages of argon were that arc starting was easier, and heat input was more stable because small changes in arc length resulted in less change in arc voltage.

To facilitate rapid withdrawal of heat from the weld zone, the housing and cover were clamped in a water-cooled copper alloy chill-block fixture that exposed only the corner to be welded (Fig. 21, detail A, Before welding). The fixture was attached to a sliding mechanism designed for easy loading and unloading of the workpiece and for positioning the joint directly under the electrode. Motion of the electrode holder was controlled by a magnetic tracing unit, which was driven by rotating a knurled magnetic pin around the edge of a steel template. An ultraviolet lamp aimed at the electrode tip provided an ionized path for easy arc starting.

Welding current was supplied by a 200-amp transformer-rectifier and the entire welding cycle was regulated by a sequence timer equipped with controls for argon preflow and postflow, arc starting and stopping, torch travel, and current downslope. Welding was done in two steps. First, one half of the joint was welded from end to end by melting the corner edge of the cover to form a smooth radius as shown in detail A, Fig. 21. The assembly was then unclamped, rotated 180°, and reclamped, and the other half was welded in the same manner. Production was 59 switches per hour.

After welding, the switch body was tested for leaks, using a leak tester of the mass-spectrometer type. If acceptable, the switch was backfilled with dry nitrogen and sealed off. If a leak was detected, a bubble test was made to locate the leak. If the leak was in the weld, the switch was rewelded and again backfilled with dry nitrogen and resealed. Rejections for defects in welding were generally below 5%.

Melt-through welding refers to the welding of a joint from one side only in a manner that provides complete joint penetration of weld metal, with visible root reinforcement. The melt-through technique is limited to the joining of relatively thin sections, and gas tungsten-arc welding is a preferred process for such applications, especially when the elements to be joined are made of stainless steel or of a nickel-base alloy. Obtaining a satisfactory weld from one side only is most advantageous when accessibility is largely limited to one side; in such applications, melt-through welding may also be more economical than conventional techniques because the amount of welding required is less. Both factors — accessibility and economy — were involved in the application described in the following example.



Item	Longitudinal weld	Circumferential weld
Process	Automatic gas tungsten-arc welding	
Joint type	Butt	Edge
Joint location	Cylinder joint	Frame to cylinder
Weld type	Square groove	Square groove
Fixtures	Backing bar(a), hold-down bars	Copper hold-down rings
Power supply	200-amp transformer-rectifier	
Electrode	1/16-in.-diam EWTh-2	3/32-in.-diam EWTh-2
Electrode taper	1/4 in. long to point	1/8 in. long to point
Nozzle diameter	3/8 in.	5/8 in.
Filler metal	None(b)	0.030-in.-diam ER308(c)
Filler-wire angle	...	30° from horizontal(c)
Filler-wire tip to electrode	...	3/8 in.(c)
Shielding gas	Helium, at 30 cfh	Helium, at 35 cfh
Backup gas	Helium, at 25 cfh	Helium, at 25 cfh
Starting-tab size	0.028 by 1.0 by 3.0 in.	None
Runoff-tab size	0.028 by 1.0 by 3.0 in.	None
Welding position	Flat	Horizontal-rolled pipe
Current (dcsp), and voltage	18.5 amp; 15 v	50 amp; 15 v
Filler-wire feed rate	...	28 ipm
Electrode extension	13/32 in.	7/16 in.
Travel speed	10 ipm	10 ipm

(a) Made of deoxidized copper. (b) Except for weld repair. (c) Applies only to circumferential welding of joint between two cylinders and supporting joint providing internal link.

Fig. 20. Precision welding of thin-skin missile-body segments that were fabricated to close dimensional tolerances and carefully cleaned before assembly and joining (Example 261)

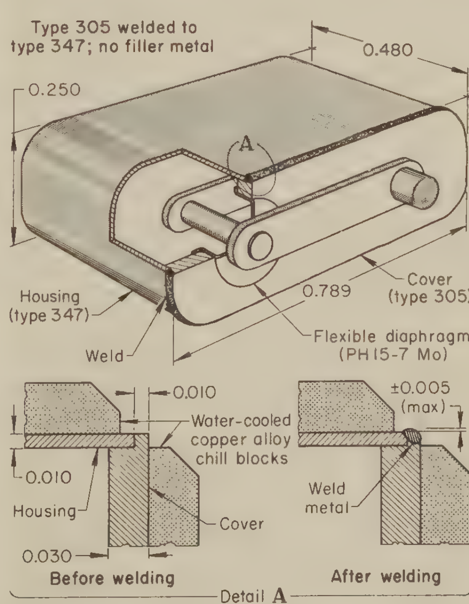


Fig. 21. Microswitch housing assembly that required close control over heat input during welding to obtain hermetic sealing between the cover and housing without damage to internal components (Example 262)

Example 263. Single-Pass Melt-Through Welding of T-Joints on a Strut-Cover Sheet Assembly (Fig. 22)

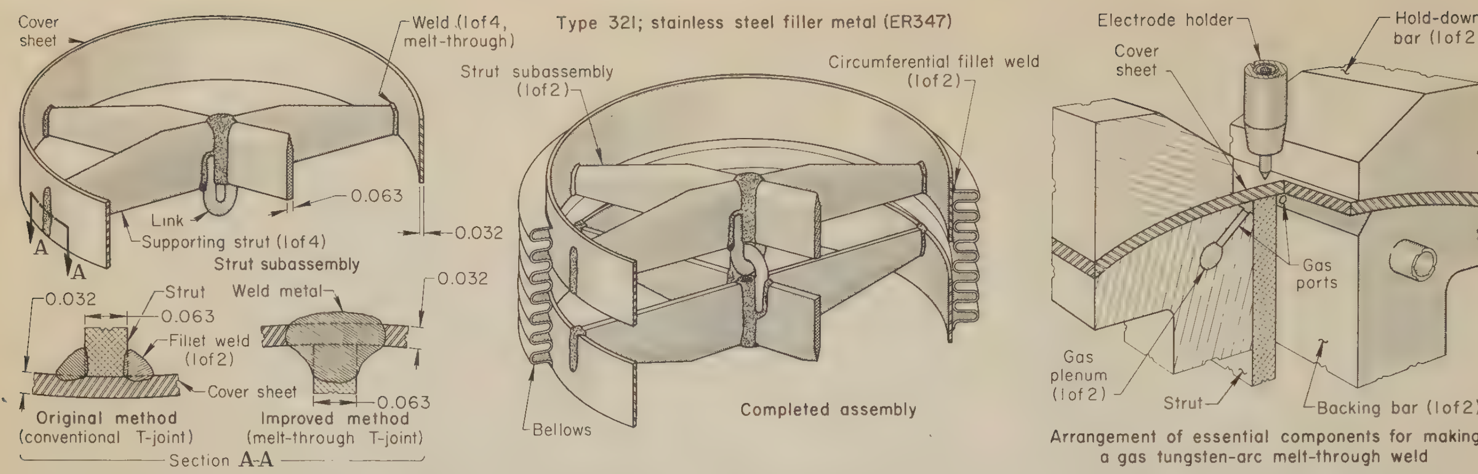
The left view of Fig. 22 shows a welded assembly consisting of a cylindrical cover sheet enclosing a central link and four supporting struts. The cover sheets of two of these assemblies were joined by circumferential fillet welds to the opposite ends of a bellows (Fig. 22, center). The completed weldment was used in an aerospace application to provide a strong, flexible connection to rigid segments of a ducting system. This example deals only with the welding of the supporting struts to the cover sheet of the assembly.

Originally, the T-joint between the ends of the struts and the inside surface of the cover sheet was made by two fillet welds deposited by the gas tungsten-arc process. Success of the welding procedure depended largely on the inside diameter of the cover sheet, which (depending on the size of the assembly) ranged from 1¼ to 8 in. As the diameter decreased, joint accessibility (for manipulation of the torch and filler metal) also decreased; as a result, weld quality was adversely affected, and meeting radiographic standards became difficult.

The difficulty was overcome by joining the cover sheets to the struts from the outside by melt-through welding. Complete joint penetration was obtained in a single pass; filler metal was added to supply the volume needed to form a double-fillet-welded T-joint (see section A-A in Fig. 22). A minimum fillet-weld size of 0.040 in. was adequate for strength.

To establish welding conditions for various combinations of work-metal thickness (ranging from 0.032 to 0.250 in.) and alloys, about 250 strut-cover sheet assemblies were joined by melt-through welding and inspected. Welding conditions for three such combinations are summarized in the table accompanying Fig. 22. A typical arrangement of components for welding is shown at the extreme right in Fig. 22.

The completed melt-through welds were found to be of excellent quality. All welds met the minimum requirements for fillet size and surface appearance. Radiographic examination, which was simplified because of the absence of discontinuities at the root of the weld, showed complete fusion and adequate joint penetration. Porosity was encountered only when preweld cleaning had been inadequate. No significant indications were noted under dye-penetrant inspection. Macrographs of weld sections showed no significant defects. Failures in



Welding condition	0.063-in. type 321 struts welded to 0.032-in. type 321 cover sheet, as shown	0.093-in. alloy A-286 struts welded to 0.063-in. type 321 cover sheet	0.188-in. Inconel 718 struts welded to 0.060-in. type 321 cover sheet
Joint cleaning	(a)	(a)	(a)
Electrode	EWTh-2	EWTh-2	EWTh-2
Filler metal	ER347	ERNiMo-6	ERNiMo-6
Shielding gas at nozzle	Argon, at 10 cfh	Argon, at 10 cfh	Argon, at 20 cfh
Backing gas	Argon, at 3 cfh	Argon, at 3 cfh	Argon, at 3 cfh
Current (dcsp)	80 amp	130 amp	140 amp
Voltage	10 v	10 v	11 to 13 v
Welding speed	3.25 ipm	2.75 ipm	3 ipm

(a) All joints were degreased, pickled, rinsed and dried before welding.

Fig. 22. Subassembly for which a change from the conventional to the melt-through technique of manual gas tungsten-arc welding for joining struts to cover sheet increased joint accessibility and improved weld quality (Example 263)

Table 9. Nominal Conditions for Gas Metal-Arc Welding of Austenitic Stainless Steel With a Spray Arc (Source: Same as Table 4)

Plate thickness, in.	Joint and edge preparation	Electrode wire diameter, in.	Current (dcrp), amp	Wire-feed speed, ipm	Welding speed, ipm	Number of passes
0.125	Square butt with backing	1/16	200-250	110-150	20	1
0.250	Single-V butt, 60° incl angle, no root face	1/16	250-300	150-200	15	2
0.375	Single-V butt, 60° incl angle, 1/16-in. root face	1/16	275-325	225-250	20	2
0.500	Single-V butt, 60° incl angle, 1/16-in. root face	3/32	300-350	75-85	5	3-4
0.750	Single-V butt, 90° incl angle, 1/16-in. root face	3/32	350-375	85-95	4	5-6
1.000	Single-V butt, 90° incl angle, 1/16-in. root face	3/32	350-375	85-95	2	7-8

peel tests occurred wholly in the base metal. Mechanical tests indicated significant improvement in fatigue life. Thus, melt-through welding not only solved the problem of how to obtain accessibility but also produced superior welds and reduced the number of welds for the assembly.

Plasma-Arc Welding

Plasma-arc welding is frequently used for joining stainless steel. The use of the process for welding stainless steel and other metals is described in the article on Plasma-Arc Welding, which begins on page 138 in this volume. Examples 143, 146 and 147 in that article deal with austenitic stainless steel; Tables 6 through 9 present welding data on stainless steel.

Gas Metal-Arc Welding

Most of the advantages of the gas metal-arc process for welding stainless steel are the same as for welding carbon steel of low carbon content. Major advantages are: (*a*) the continuously fed electrode wire permits long, uninterrupted periods of welding; (*b*) the process can be readily automated; (*c*) the use of shielding gas instead of a flux eliminates the need for slag removal and enables the operator to watch the welding operation; and (*d*) low-hydrogen deposits are obtained without the need for baking the electrodes (as may be required in shielded metal-arc welding). Also, the gas metal-arc process offers a variety of means by which transfer of weld metal can be effected: spray arc, short-circuiting arc, and pulsed arc.

Limitations of the process are also essentially the same for welding stainless steel as for welding low-carbon steel. Compared with shielded metal-arc welding, the equipment costs more and is less portable, and gas metal-arc operations must be shielded from drafts. For details of the process, see the article on Gas Metal-Arc Welding, page 78 in this volume.

Welding Current. The polarity of the welding current used in gas metal-arc welding depends primarily on the penetration desired. The greatest penetration is obtained with reverse polarity (electrode positive). Regardless of whether the electrons impinge on the electrode wire (as in reverse polarity) or on the work (as in straight polarity), heat builds up in the base metal through the metal drops. Reverse polarity results in the metal drops being subjected to considerable force by the positive ions of gas, resulting in deep penetration. Conversely, when straight polarity is used, the force exerted on the metal drops by the gas ions tends to support them, resulting in shallow penetration. It is estimated that more than 95% of all gas metal-arc welding of stainless steel is done using reverse-polarity direct current, straight polarity being restricted to applications requiring shallow penetration.

Because the electrical resistivity of stainless steels is greater than that of carbon steels, the electrode melting rate is higher for a given electrode stickout. Allowing for some variation among different grades, the same deposition rate can be achieved for stainless steels at about 80% of the current required for plain carbon steels, other conditions being the same. Some typical current values for specific conditions are given in Tables 9 and 10.

Table 10. Nominal Conditions for Gas Metal-Arc Welding of Austenitic Stainless Steel With a Short-Circuiting Arc (Source: Same as Table 4) (a)

Plate thickness, in.	Joint and edge preparation	Electrode wire diameter, in.	Current (dcrp), amp	Voltage, v	Wire-feed speed, ipm	Welding speed, ipm	Number of passes
0.063	Nonpositioned fillet or lap	0.030	85	21	184	18	1
0.063	Butt (square edge)	0.030	85	22	184	20	1
0.078	Nonpositioned fillet or lap	0.030	90	22	192	14	1
0.078	Butt (square edge)	0.030	90	22	192	12	1
0.093	Nonpositioned fillet or lap	0.030	105	23	232	15	1
0.125	Nonpositioned fillet or lap	0.030	125	23	280	16	1

(a) With a shielding gas containing 90% helium, 7.5% argon and 2.5% carbon dioxide

Spray Transfer. High current density is the principal requirement for spray transfer of metal from the electrode to the base metal. At a certain minimum current density, which varies with electrode size and material, metal transfer through the arc changes from very large globular drops, which fall off the end of the electrode, to a stream of extremely fine droplets axially projected from the end of the electrode. The metal transfer changes from a fluttering, erratic discharge with a wandering cathode spot to a steady, quiet arc column. This arc column is a well-defined, narrow, incandescent, cone-shape core within which metal transfer takes place. Because the method utilizes high current and voltage, the weld puddle is quite fluid (limiting welding to the flat or horizontal position). Deposition rates are high, penetration is deep when reverse polarity is used, and the arc is exceptionally stable. The minimum thickness of stainless steel that can be satisfactorily welded using spray transfer is about ⅛ in. Generally, it is used on materials ranging from ¼ to 1 in. in thickness. The diameter of electrode wire for spray transfer is usually 0.045 to 3/32 in. (Table 9).

On square-butt welds, a backing strip should be used to prevent weld drop-through. When fit-up is poor or copper backing cannot be used, a short-circuiting transfer for the root pass will minimize drop-through.

Short-Circuiting Transfer. Welding with a short-circuiting arc employs lower current, generally ranging from 50 to 225 amp, low voltages of 17 to 24 volts, and small-diameter wires — 0.030, 0.035 and 0.045-in. diameters being the popular sizes. The distinctive feature of the short-circuiting arc is the frequent shorting of the electrode wire to the work. All metal transfer takes place at arc outages, which occur at a steady rate and can vary from 20 to more than 200 per second. The net result is a stable arc of low energy and heat input, ideally suited to the welding of thin sections in all positions. The low heat input minimizes work-metal distortion. The short-circuiting arc is better than the spray arc for welding joints that have poor fit-up.

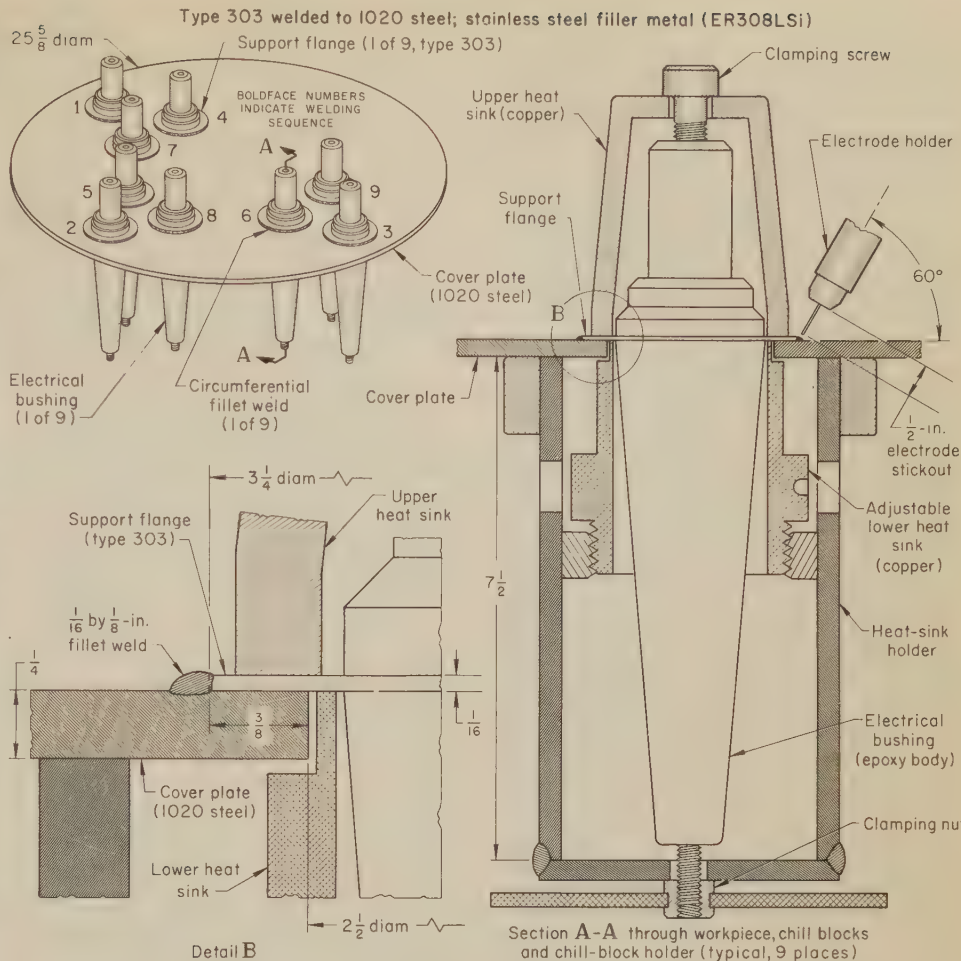
The short-circuiting characteristic cannot be obtained for the full range of operation with ordinary or conventional power-supply units. Machines are available that contain slope, voltage, and inductance adjustments suitable for producing the controlled current surges needed to implement short-circuit transfer on stainless steel. Inductance, in particular, plays an important part in obtaining proper puddle fluidity when short-circuiting transfer is used on stainless steel.

Electrode-wire extension (stickout) should be kept as short as possible. Backhand welding is normally easier on fillet welds and results in cleaner welds. Forehand welding is used for butt welds; outside corner welds are made with a straight motion. Table 10 gives typical welding conditions.

Pulsed-arc transfer is a spray-type transfer occurring in pulses at regularly spaced intervals rather than at random intervals. In the time interval between pulses, the welding current is reduced and no metal transfer occurs.

Pulsing is obtained by combining two current levels provided by two separate power supplies. One power supply provides a background current to preheat and precondition the advancing (continuously fed) electrode wire; the other supplies a peak current for forcing the drop of molten filler metal from the electrode to the workpiece. Drops are transferred 60 times (or multiples of 60 times) per second, because the peak current is tied in with the line frequency.

Electrode wire diameters of 0.045 to 1/16 in. are most commonly used for pulsed-arc transfer welding of stainless steels. Because of the lower heat input, the process is capable of welding sections thinner than are practical to weld by conventional spray transfer; work-metal distortion is also lower, as in the example that follows.



Item	Spray-arc transfer	Pulsed-arc transfer
Process	Automatic gas metal-arc welding	
Joint type	Lap	Lap
Weld type	Fillet	Fillet
Fixtures	Copper chills(a)	Copper chills(a)
Power supply	500-amp transformer-rectifier(b)	250-amp dual transformer-rectifier
Electrode holder	....	200 amp, air cooled
Electrode	0.035-in.-diam ER308L(Si)(c)	0.035-in.-diam ER308L(Si)(c)
Shielding gas	98% A – 2% O_2	98% A – 2% O_2, at 30 to 40 cfh
Number of passes	One	One
Arc length	....	3/32 in.
Current (dcsp)	200 to 225 amp	110 to 115 amp
Voltage	....	24 v (background); 38 v (pulse)(d)
Electrode-feed rate	Dial adjustable	360 ipm
Electrode stickout	....	½ in.
Pulse frequency	....	60 Hertz
Welding speed or time	22 ipm	30 sec per pass

(a) Rotatable three-jaw chuck; manipulator boom. (b) With slope control. (c) Low-carbon, high-silicon ER308L(Si) electrode was selected to minimize base-metal dilution and for ease of deposition. (d) Maximum setting of pulse voltage is 38 volts; peak near 50 volts.

Fig. 23. Sequence and arrangement of fixtures for welding joints between electrical bushings and a cover plate, which required careful control of heat input and weld-bead size to minimize distortion and leakage (Example 264)

Example 264. Change From Spray Transfer to Pulsed-Arc Transfer and the Use of Heat Sinks To Minimize Distortion and Leakage (Fig. 23)

Excessive distortion and leakage were encountered in welding the supporting flanges of electrical bushings to the cover plate of a switching device (see Fig. 23, upper left). The supporting flanges, consisting of 1/16-

in.-thick type 303 stainless steel disks molded to the epoxy body of the electrical bushings, were joined to the 1020 carbon steel cover plates (¼ in. thick) by a single-pass circumferential fillet weld. The principal requirements were that the welds be leaktight under an air pressure of 5 psi and that the cover remain flat, as any distortion of the subassembly would cause misalignment and malfunctioning of parts to be installed later. The problem of distortion was further complicated by the number and arrangement of bushings in the cover and by differences in thermal conductivity and expansion of the two metals being welded.

Originally, ⅛-in. fillet welds were deposited at the joint between the flange and cover plate by automatic gas metal-arc welding with spray transfer, under conditions listed in the table accompanying Fig. 23. The procedure had to be abandoned because even the smallest welds deposited by this procedure were oversize in relation to the nominal 1/16-in. size of the joint and resulted in excessive heat buildup and distortion of the welded components.

To reduce heat buildup in the subassembly, copper heat sinks were placed on either side of the flange, as shown in Fig. 23. The upper heat sink, consisting of a heavy thimble-shape cap, was held firmly against the flange by a clamping screw; the lower heat sink was placed inside a 4-in.-diam schedule 80 pipe and held in place by an adjustable clamping nut. The copper heat sinks were used in pairs and alternated with other pairs, the working pair being removed and cooled in water after two successive runs.

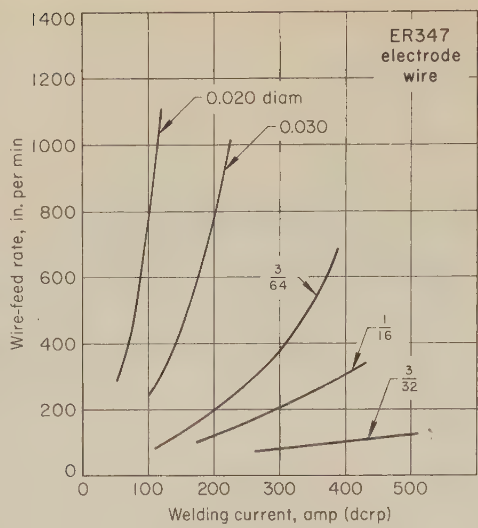
Before welding, the pipe was clamped vertically in a rotatable three-jaw chuck (not shown in Fig. 23); the cover plate was positioned over the pipe; and the bushing hole centered. The bushing was then inserted in the cover and the assembly was drawn up tight by the clamping nut at the bottom. The upper heat sink was fastened in place, and the bottom (adjustable) heat sink was run up with a special wrench, through circumferential slots in the pipe. The electrode holder and wire drive, which were mounted on a manipulator boom, were adjusted so that the electrode holder maintained a 60° angle with the horizontal during welding (see Fig. 23, section A-A).

Heat dissipation was assisted by welding the nine joints in the numerical sequence shown in Fig. 23 (upper left).

Although the use of heat sinks and sequential welding reduced distortion to an acceptable level, about 80% of the weldments still showed small leaks during air testing. Inadequate joint penetration at the overlap of the start and finish of the weld and fast cooling of the oversize bead were suspected to be responsible for the leaks.

The difficulties were overcome by changing to pulsed-arc transfer using a 250-amp dual rectifier and the same setup of equipment for heat dissipation from the weld zone as described earlier. Welding conditions are shown in the table with Fig. 23. With pulsed transfer, penetration was satisfactory and a smaller bead with a lower heat input was obtained. Distortion was further reduced and rejections for leaks were decreased to about 20%.

Electrode Wires. The electrode wire diameters for gas metal-arc welding are generally between 0.030 and 3/32 in. For each wire diameter, a certain minimum welding current must be exceeded to achieve spray transfer. For example, when welding stainless steel in an argon-oxygen atmosphere with a 3/64-in.-diam stainless steel electrode wire, spray transfer will be obtained at a welding current of about 225 amp, dcrp. Figure 24 illustrates typical deposition rates and welding current values for various sizes of ER347 electrode wires, using a mixture of argon with 1% oxygen as the shielding gas. With the minimum current, a minimum arc voltage must also be used. This is generally between 25 and 30 volts.



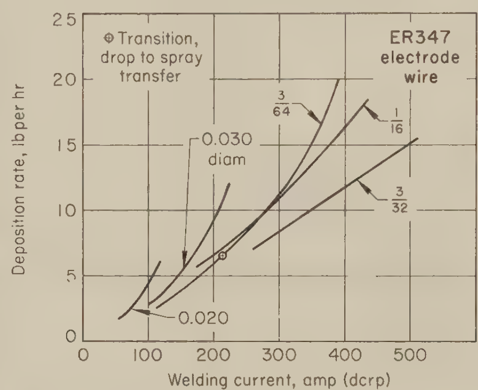


Fig. 24. Relations of welding current to deposition rate for various sizes of ER347 electrode wires. Shielding gas, argon plus 1% oxygen.

Table 11 lists 17 austenitic and precipitation-hardening stainless steel base metals and the electrode wires recommended for welding them. Electrode wires made of high-silicon austenitic stainless steel and wires for welding straight-chromium stainless steel are also available. The austenitic wires with higher silicon content have particularly good wetting characteristics when they are used with short-circuiting transfer.

Shielding Gases. Although the range of choice of shielding gas for welding stainless steels is considerably narrower than for carbon and low-alloy steels, several gas mixtures have proved satisfactory. The mode of metal transfer influences the choice of shielding gas. For instance, with spray-arc or pulsed-arc transfer, a shielding-gas mixture containing 99% argon and 1% oxygen has been widely used and generally recommended. In some plants, 98% argon and 2% oxygen is used with success (see Example 264).

Table 11. Recommended Electrode Wires for Gas Metal-Arc and Submerged-Arc Welding of Austenitic and PH Stainless Steels

Base metal	Filler metal	Base metal	Filler metal
301, 302	ER308	317	ER317
304	ER308	330	330
308	ER308	321	ER321
304L	ER308L	347	ER347
309	ER309	17-7 PH Mo	17-7 PH
310	ER310	17-4 PH	PH 15-7 Mo
316	ER316	AM-350	AM-350
316L	ER316L	AM-355	AM-355

SOURCE: Same as Table 4

For short-circuiting transfer, a mixture of 90% helium, 7.5% argon, and 2.5% carbon dioxide has been extensively used for shielding (see Example 265); but helium is gradually losing favor because of its high cost. However, a mixture in which the above proportions of helium and argon have been reversed — that is, 90% argon, 7.5% helium, 2.5% carbon dioxide — has proved successful for short-circuiting transfer (see Example 266).

Regardless of other variations, the shielding gas for gas metal-arc welding of stainless steel should contain at least 97.5% inert gas (argon or helium, or a mixture of the two). When carbon dioxide is used, the maximum is usually 2.5%, to retain weld quality and corrosion resistance.

Automatic Gas Metal-Arc Welding. A principal advantage of the gas metal-arc process over shielded metal-arc welding is that it is automatic or semiautomatic. Although this advantage prevails in the welding of carbon steel as well as stainless steel, the degree of control that can be achieved with automatic welding makes it especially appropriate for the welding of stainless steel. Specific applications are described in the two examples that follow.

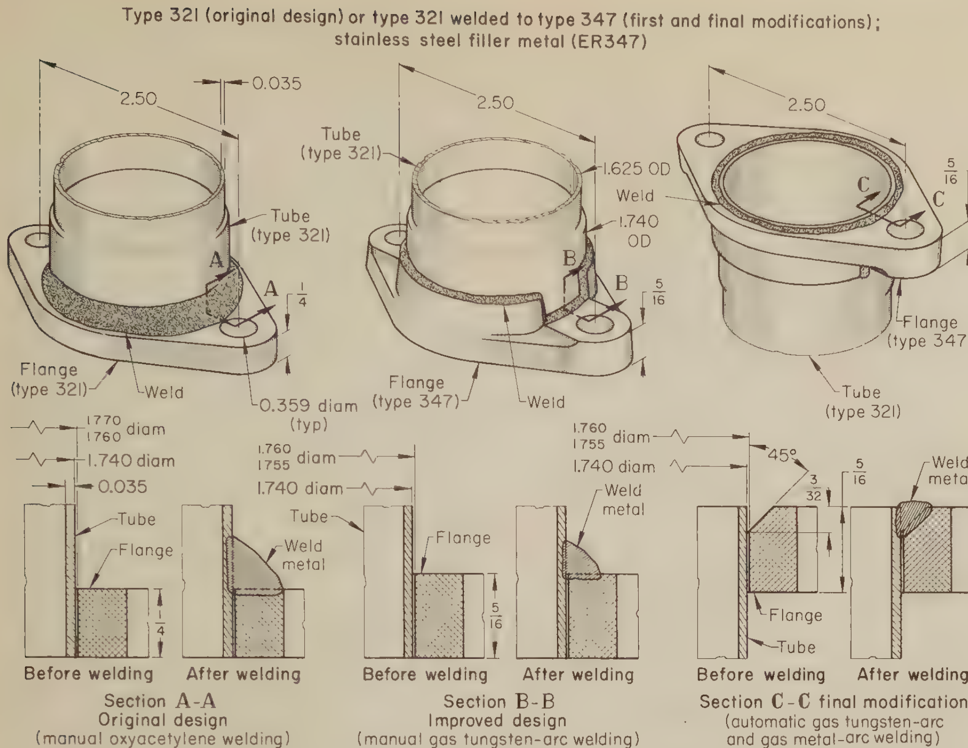
Example 265. Change From Oxyacetylene to Gas Tungsten-Arc to Automatic Gas Metal-Arc Welding for Increased Quality and Production Rate (Fig. 25)

The tube-and-flange assemblies shown in Fig. 25 served as part of the exhaust system for a small reciprocating-type aircraft engine. Specifications required that the joint between the thin-wall stainless steel tube and the mounting flange be of adequate strength, free from leaks, and with alignment accurate enough to permit minimal machining of the flange face and the bolt-head seat.

The original flange design shown in Fig. 25 (left) consisted of a ¼-in. flat flange of type 321 stainless joined to a 0.035-in.-wall tube of the same material. The tube was expanded from 1.625-in. OD (0.035-in. wall) to 1.740-in. OD for a distance of 1 in. at the joint. A single-pass circumferential fillet weld was made by oxyacetylene welding with a 1/16-in.-diam rod of type 347 stainless steel and a proprietary flux. Inspection of the weld resulted in some rejections because of distortion and crack indications in fluorescent-particle testing. Moreover, welding speed (average welding time was 7 min per weld) was necessarily low, to prevent burn-through of the thin-wall tube and to avoid overwelding at the points requiring bolt-head clearance.

Improved results were obtained by welding the same flange and tube joint by the manual gas tungsten-arc process. Using a 250-amp dc power supply having a foot-operated current control, a light-duty electrode holder, low welding current, and ER347 filler metal, a single-pass weld was made in an average time of about 5 min. Argon shielding was used at the torch and argon purging inside the tube assembly. This process produced less distortion and fewer weld defects than did oxyacetylene welding. However, results were still not acceptable.

To eliminate distortion, flange design was changed. The hub-type flange, slotted for bolt-head clearance as shown in Fig. 25 (center), was made of type 347 stainless steel, and was provided with a thicker cross section to resist distortion. The hub



Conditions for Automatic Gas Metal-Arc Welding

Joint type	Corner
Weld type	45° single-bevel groove
Fixtures	Adjustable torch holder, turntable, assembly fixture
Power supply	300-amp, constant-potential transformer-rectifier(a)
Electrode holder	Fixed machine type
Electrode	0.030-in.-diam ER347
Shielding gas	90% helium, 7.5% argon, 2.5% CO_2; at 15 cfh
Welding position	Flat
Number of passes	One
Voltage	25 v
Electrode-feed rate	216 ipm
Mode of transfer	Short circuiting
Electrode stickout	⅜ in.
Preheat	None
Welding speeds for all processes (different designs):	
Gas welding (section A-A)	¾ ipm
Gas tungsten-arc (section B-B)	1.1 ipm
Gas metal-arc (section C-C)	30 ipm

(a) With variable slope control

Fig. 25. Original, improved, and final modified designs and welding procedures for flange-to-tube joint (Example 265)

(including the sides and bottom of the slotted portions) was welded all around by the gas tungsten-arc process. Although there was no distortion, welding time was increased and difficulty was encountered in leaving bolt-head clearance when making the weld in the small slotted area.

To overcome this difficulty, the circumferential part of the weld was transferred from the hub to the face of the flange, as shown in Fig. 25 (right), the welds on the vertical sides of the slots being retained. The weld was deposited in a groove formed by a 3⁄32-in., 45° bevel. Part alignment and bolt clearance were satisfactory; there were no difficulties in machining the face of the flange, and dye-penetrant inspection indicated very few flaws.

Because the weld was circular and easily accessible, the gas tungsten-arc process was readily automated, using an adjustable torch mount, wire-feed drive and a rotatable turntable. To obtain a consistently small weld bead without burn-through or overlapping in the thin tube wall, voltage was automatically controlled, but despite the automation of equipment, the bead contour was insufficiently uniform.

Finally, automatic gas metal-arc welding with short-circuiting transfer was tried. The low heat input of the process allowed a small weld bead of the desired contour to be consistently deposited at a rate of 30 ipm. Argon purging of the inside of the tube was no longer needed. Once the machine settings were established, parts were welded with repetitive accuracy, meeting all specification requirements. A simple welding fixture was constructed to align the flange with the tube and to hold the assembly in position during welding. Supplementary tests showed that the welds on the vertical sides of the hub slots could be eliminated, reducing production time further. Welding conditions for the process are given in the table accompanying Fig. 25. Fluctuations in line voltage had no serious effect, because at the low voltages used, only minor adjustments in the power supply were required.

Example 266. Full-Penetration Weld in 0.045-In.-Wall Tubing by Automatic Gas Metal-Arc Welding (Fig. 26)

Obround tubing for use in low-pressure heat exchangers was formed from 0.045-in.-thick type 304 stainless steel sheet, and welded along the longitudinal seam as shown in Fig. 26. The principal objective was to obtain a sound weld with full penetration, at low cost and a high production rate. By automatic gas metal-arc welding with short-circuiting transfer, full-penetration welds were obtained (at a welding speed of 30 ipm) with relatively simple equipment and tooling.

The tubing was formed from a stainless steel sheet 8 ft long and 0.045 in. thick. The as-sheared square-butt joints were brushed with a stainless steel wire brush and wiped with a solvent cleaner. The 8-ft length of tubing was placed between the jaws of a hydraulically operated clamping fixture, which forced the joint edges together along the full length of the seam. Starting and runoff tabs, about ½ in. square, of the same material and thickness as the base metal, were tack welded in place to ensure sound weld metal at the tube ends (see Fig. 26).

The electrode holder, wire-feed drive and filler-metal coil (ER308) were mounted on a motor-driven carriage that traveled on a horizontal track above the joint. Welding was done in a single continuous pass (see the welding conditions in the table that accompanies Fig. 26).

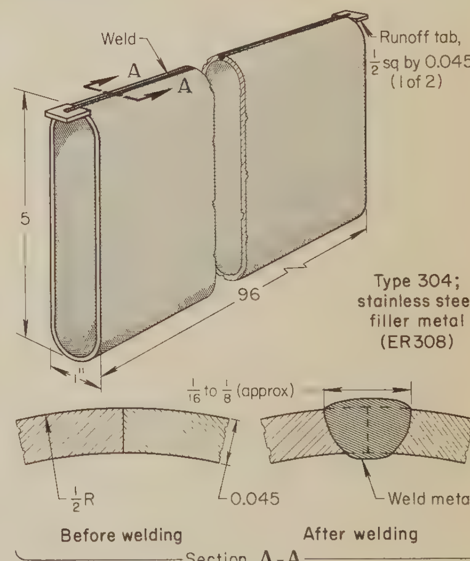
The significant variables in the process were joint fit-up, wire feed and travel speed. Some burn-through occurred, which required repair welding, but rejections resulting from this cause amounted to less than 2%, a figure considered acceptable.

After welding, completed tubes were inspected visually for continuity and soundness, and were leak tested at an air pressure of 5 psi under water. Qualification tests for the welding procedure and for operators were conducted according to Section IX of the ASME code.

Shielded Metal-Arc Welding

The shielded metal-arc process ("stick electrode" manual welding) is widely used for welding stainless steel. Its principal advantage is flexibility. For a description of the process, see the article on Shielded Metal-Arc Welding, which begins on page 1 of this volume.

The disadvantages of shielded metal-arc welding are: (*a*) the slag blanket constitutes a potential source of inclusions; (*b*) control of weld-metal deposition requires more skill than is needed in gas-shielded arc welding; (*c*) visibility during welding is impaired by slag; (*d*) slag removal between passes is necessary; (*e*) the process is not adaptable to very thin



Process	Automatic gas metal-arc welding(a)
Joint type	Butt
Weld type	Square groove
Fixtures	Seam-alignment clamp, torch carriage(b)
Power supply	300-amp constant-potential dc transformer-rectifier(c)
Electrode holder	Machine type, water cooled
Electrode	0.035-in.-diam ER308
Shielding gas	90% argon, 7.5% helium, 2.5% CO_2; at 15 cfh
Welding position	Flat
Number of passes	One
Current	85 to 95 amp, dcrp
Voltage	14 to 15 v
Electrode-feed rate	200 to 240 ipm
Electrode stickout	½ in.
Preheat and postheat	None
Welding speed	30 ipm

(a) With short-circuiting transfer. (b) Arc starting and runoff tabs were used. (c) Slope and reactance controls.

Fig. 26. Obround tube for a heat exchanger made by forming and seam welding (Example 266)

Table 12. Electrodes for Shielded Metal-Arc Welding of Austenitic Stainless Steel

For use with reverse-polarity direct current (dcrp) only		
E308-15	E310(Cb)-15	E317-15
E308L-15	E310(Mo)-15	E318-15
E309-15	E312-15	E320-15
E309(Cb)-15	E16-8-2-15	E330-15
E309(Mo)-15	E316-15	E347-15
E310-15	E316L-15	E349-15
For use either with alternating current or with dcrp		
E308-16	E310(Cb)-16	E317-16
E308L-16	E310(Mo)-16	E318-16
E309-16	E312-16	E320-16
E309(Cb)-16	E16-8-2-16	E330-16
E309(Mo)-16	E316-16	E347-16
E310-16	E316L-16	E349-16

SOURCE: Same as Table 4

sections; and (*f*) electrodes are sensitive to moisture pickup. Because of the requirements for corrosion resistance that normally apply, these disadvantages must be taken into account in the welding of stainless steel.

Constant-current (drooping-voltage) power sources, conventionally used for shielded metal-arc welding, are applicable for welding stainless steel. Either alternating current or reverse-polarity direct current is suitable in most applications. Direct-current power supply can be of the motor-generator or transformer-rectifier type.

Electrodes. Table 12 lists austenitic stainless steel electrodes used for shielded metal-arc welding. The suffix number is related to the polarity to be used. The suffix -15 indicates that the coating is primarily of the lime type, containing a fair amount of calcium or other alkaline elements, and that the electrodes are suitable for use with reverse-polarity direct current. For welding with alternating current, an electrode with the suffix -16 should be selected. Such electrodes can be used with reverse-polarity direct current as well and can have either a lime-type or titania-type covering. For welding with alternating current, the coating, besides having alkaline elements, also contains readily ionized elements to stabilize the arc. The designation E16-8-2 refers to the chromium, nickel and molybdenum contents of electrodes not otherwise identifiable by the AISI system of designations.

Electrodes of the -15 and -16 types up to 5⁄32 in. in diameter can be used in all welding positions; electrodes 3⁄16 in. in diameter and larger, in the flat and horizontal fillet positions only.

The electrodes listed in Table 12 cover most requirements for welding the standard austenitic grades and, to a large extent, the straight chromium grades (martensitic and ferritic), depending mainly on whether the weldments will be subjected to postweld heat treatment or not. Suggested electrodes for welding the austenitic, martensitic and ferritic grades are given in Table 1. In applications where the mechanical properties of welded joints are not critical, the precipitation-hardening steels can be welded with standard austenitic electrodes.

For welding special grades of stainless steel, it may be necessary to use composite electrodes of special composition. For shielded metal-arc welding, a composite electrode consists of a flux-covered carbon steel tube containing the alloying elements, in powder form, in the core. These electrodes are available for depositing the standard compositions of stainless steel.

The example that follows describes an application that required the use of a composite electrode.

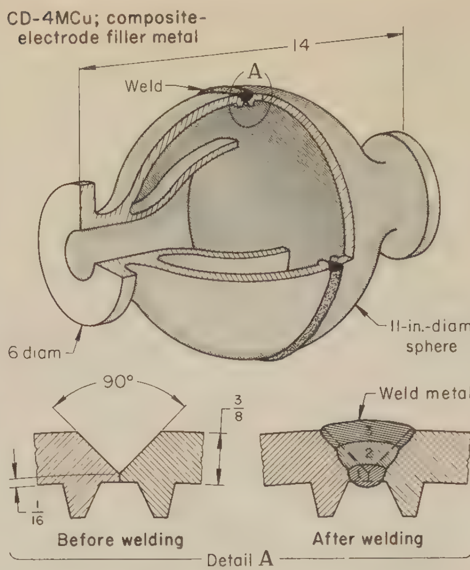
Example 267. Use of a Composite Electrode To Weld Two Stainless Steel Castings (Fig. 27)

Air separators for self-priming pumps to be used in a corrosive medium were cast from high-strength CD-4MCu stainless steel in the form of hemispheres and were joined at the equator by shielded metal-arc welding, as shown in Fig. 27. The composition of the austenitic-ferritic (CD-4MCu) stainless steel castings was: 0.04 C max, 1.0 Mn max, 1.0 Si max, 24.5 to 26.5 Cr, 4.75 to 6.0 Ni, and 1.75 to 2.25 Cu. Minimum mechanical properties were: tensile strength, 100,000 psi; yield strength, 70,000 psi; and elongation in 2 in., 20%.

Because no standard filler metal was available to match the base-metal composition, a composite electrode was formulated. Low-carbon steel tubes were filled with alloy powder in proportions that would produce a deposit equivalent in composition to the base metal. The electrodes were manufactured as follows: carbon steel strip was partially roll formed and filled with the alloy powder. Roll forming was continued until the tube was tightly closed and crimped, after which it was pulled through dies to reduce the outside diameter of the tube to 5⁄32 in., and it was cut to length. The tubes were then processed through a press that extruded a flux covering concentric with the tube.

The hemispheres (of 3⁄8-in. wall thickness, 11-in. diameter and 7-in. height) were cast with 45° bevels at the joint edges (see Fig. 27 for joint details). Casting skin at the joint edges was removed by grinding, and the parts were assembled in a lathe-type positioner for flat welding. Welding was accomplished in three passes under the conditions listed in the table with Fig. 27. Welds were carefully cleaned between passes, using a stainless steel wire brush. The width of weave was not permitted to exceed four times the electrode diameter — that is, 5⁄8 in. max.

After welding, the assembly was solution heat treated to obtain maximum corrosion resistance. Following heat treatment, the weldments were sand blasted, machined, and pressure tested with air at 100 psi.



Process	Shielded metal-arc welding
Joint type	Circumferential butt
Weld type	90° V-groove
Fixture	Rotating positioner
Power supply	300-amp, dc motor-generator
Electrode	5⁄32-in.-diam composite(a)
Welding position	Flat
Number of passes	Three
Current	130 amp, dcrp
Voltage	24 v
Preheat	None
Postheat	(b)
Travel speed	5 to 8 ipm

(a) A composite electrode having a flux covering and an alloy powder core formulated to deposit a weld of the same composition as the base metal. (b) Heated to 2050 F in a furnace, then furnace cooled to within the range of 1750 to 1900 F, held for ½ hr, and quenched in water.

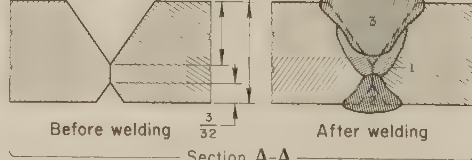
Fig. 27. Air separator for a self-priming pump used in corrosion service, fabricated by welding together two hemispheres (Example 267)

General Welding Procedure. In general, the procedure used for welding plain carbon steel of low carbon content is followed for welding stainless steels, although the differences in physical and chemical properties may necessitate modifications. Because most stainless steels have a higher coefficient of thermal expansion than carbon steels, distortion in welding is likely to be greater. On the other hand, the lower thermal conductivity of stainless steels and their higher electrical resistivity permit greater deposition rates at the same current.

When welding stainless steels, it is especially important that the weld area be clean and free of foreign matter. Organic material on the surface can break down in the heat of the arc and cause porosity and carburization of the weld metal.

The workpieces should be carefully prepared and fitted. Thin-gage stainless steel, especially, should be properly clamped and held in alignment to reduce the probability of buckling.

Large electrodes (more than ¼ in. in diameter) and excessive arc length will contribute to loss of chromium in the weld deposit. Excessive weaving of electrodes of any size should be avoided;



Pass number	Current (dcrp), amp	Voltage, v	Welding speed, ipm
1	400	26	20
2	420	28	20
3	450	32	18

Electrode: 3⁄32-in.-diam ER308; neutral flux, 12 × 150.

Fig. 28. Typical joint design and welding conditions for submerged-arc butt welding of ½-in.-thick plates of type 304 stainless steel. (See text for discussion.)

maximum width of weave should be limited to four times the core-wire diameter. In general, the stringer-bead technique is recommended.

Special care is required between weld passes to remove all slag from the deposited bead. Only stainless steel wire brushes and tools should be used for this purpose. If grinding wheels are used, the wheels should not have been contaminated by use on metals other than stainless steel.

Discoloration on either side of the weld metal by a thin oxide layer is a harmless surface condition. It can be removed by pickling, sand blasting, or power brushing, or by electrolytic cleaning if a bright surface is required.

Care in the storage of electrodes is important. Electrode coatings pick up moisture, which may lead to weld porosity. Electrode manufacturers generally supply stainless steel electrodes in moistureproof packages to prevent moisture pickup. Electrodes exposed to air and humidity can sometimes be restored to their initial condition by baking, as explained in the section on Effect of Moisture on Electrode Coverings in the article "Shielded Metal-Arc Welding" in this volume. It is best not to use such restored electrodes for critical welding applications. No attempt should be made to restore electrodes that are wet; they should be discarded.

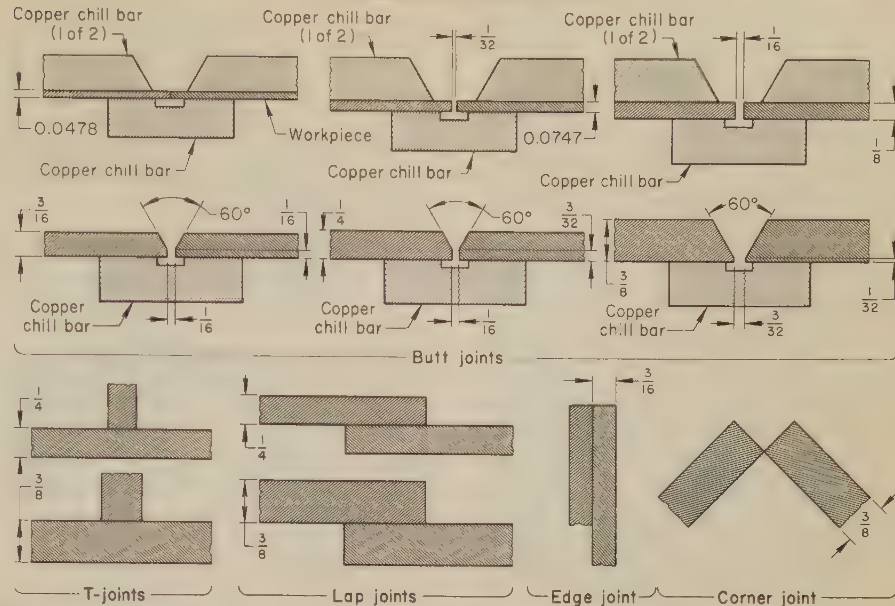
Typical welding conditions for several metal thicknesses and types of joints are given in Table 13. The illustrations in Table 13 for butt welding of austenitic stainless steel sheet and plate show copper chill bars for all base-metal thicknesses, with chill bars on both top and bottom for base-metal thicknesses less than 3/16 in.

Welding the Austenitic Steels. Austenitic stainless steels should be welded in the annealed condition. Because the austenitic steels are not hardenable by heat treatment, preheating is rarely used. Their mechanical properties are not substantially changed by welding, although stainless steel that has been purposely work hardened to increase its strength will be softened in the heat-affected zone.

For welding in the flat position, the stringer-bead technique should be used for the first pass; when the fit-up is poor, a slight weave may be required. For succeeding passes, stringer beads or a slight weave should be used. The arc should be no longer than 1/8 in. For vertical-down welding, the same technique is used, but with the electrode tilted so that the force of the arc pushes the molten metal back up the joint. Vertical-up welding calls for a triangular weave with 5/32-in.-diam or smaller electrodes. A shelf is made at the bottom of the joint (lower end) and succeeding passes are made using a slight weaving motion with the electrode pointed slightly upward. Overhead welding requires a whipping technique and a slightly circular motion. Weaving should be avoided. The arc should be as short as possible and the movement should be rapid.

Welding the Straight-Chromium Grades. Straight-chromium (ferritic or martensitic) stainless steels differ somewhat in welding characteristics from the austenitic steels because they

Table 13. Typical Joint Designs and Conditions for Shielded Metal-Arc Welding of Austenitic Stainless Steel



Base-metal thickness, in.	Pass No.	Electrode wire diameter, in.	Current, amp	Welding speed, ipm	Deposited metal, lb/ft of weld
Butt Joints(a)					
0.047	1	5/64	45	15	0.020
0.074	1	3/32	60	12	0.038
1/8	1	1/8	90	9	0.08
3/16	1	5/32	125	7	0.150
1/4	1	5/32	125	3.5	0.34
	2(b)	3/16	160	...	...
3/8	1	5/32	125	2.4	0.51
	2	3/16	160	...	...
	3(b)	3/16	160	...	...
T-Joints					
0.047	1	5/64	45	9	0.034
0.074	1	3/32	60	9	0.052
1/8	1	1/8	90	9	0.079
3/16	1	5/32	125	7	0.149
1/4	1	3/16	160	5.5	0.262
3/8	1(c)	3/16	160	3.5	0.40
	2	3/16	160	...	...

Base-metal thickness, in.	Pass No.	Electrode wire diameter, in.	Current, amp	Welding speed, ipm	Deposited metal, lb/ft of weld
Lap Joints					
0.047	1	5/64	45	13	0.023
0.074	1	3/32	65	13	0.036
1/8	1	1/8	90	13	0.056
3/16	1	5/32	125	10	0.105
1/4	1	3/16	160	6.5	0.22
3/8	1(c)	3/16	160	4.2	0.34
	2	3/16	160	...	...
Edge Joints					
0.047	1	5/64	45	20	0.015
0.074	1	3/32	60	18	0.025
1/8	1	1/8	90	15	0.047
3/16	1(c)	5/32	125	12	0.087
Corner Joints					
0.047	1	5/64	45	19	0.016
0.074	1	3/32	60	15	0.028
1/8	1	1/8	90	13	0.057
3/16	1	5/32	125	11	0.094
1/4	1	3/16	160	7	0.21
3/8	1	3/16	160	3.5	0.40
	2	3/16	160	...	...

(a) Maximum buildup of weld deposit is 1/16 in. Groove in lower copper chill bar (see drawing) is 3/16 in. wide and 1/16 in. deep. (b) Slight weaving is used. (c) A very slight weave is used. SOURCE: Same as Table 4

have a lower coefficient of thermal expansion — about the same as ferritic carbon steel. Therefore, warpage and distortion are less likely to occur. The ferritic stainless steels may become embrittled during welding and require control over preheat and postheat. (See the sections on ferritic and martensitic stainless steels, page 248 in this article.)

Submerged-Arc Welding

Among the advantages of submerged-arc welding are high deposition rate and high welding speed, which result in good economy. The principal disadvantage of the process is its inflexibility. Most installations are mechanized, although semiautomatic welding is possible. The use of flux to shield the weld requires flux handling and slag removal operations. Moreover, submerged-arc welding is restricted to the flat and horizontal positions.

For a detailed description of the process, see the article on Submerged-Arc Welding, page 46 in this volume.

Weld Quality. The quality of welds made by the submerged-arc process is generally high, but some conditions restrict use of the process. Generally, the composition of the weld metal is more difficult to control with submerged-arc welding than it is with gas tungsten-arc, plasma-arc, or electron beam welding. The heat input can be much greater than in other arc welding processes, and solidification of the weld metal is generally slower. These conditions can raise problems in welding stainless steel that are not encountered when welding carbon steel. For instance, the silicon content of the weld metal may be much higher in submerged-arc welding than in other processes, and increased silicon content may cause hot shortness or fissuring. Basic-type flux minimizes this effect.

When the weld deposit must be fully austenitic, or when the ferrite content of the deposit must be controlled to less than 4%, the risk of microfissuring is considerable, particularly in welding heavy sections, which are generally well suited for welding by the sub-

merged-arc process. The welding of relatively thick sections of type 347 stainless steel also presents a problem; service failures have occurred because of strain-induced precipitation of columbium carbides in the heat-affected zone during postweld heat treatment or service at elevated temperature.

Welding Current. Direct current is normally used for welding thin sections. For welding thicker sections, either alternating or direct current can be used. Current for welding stainless steel is usually about 80% of that used for welding carbon steel, section thickness and other conditions being the same. Some typical values of current for specific welding conditions are given in the table with Fig. 28. There are, however, conditions where alternating and direct currents cannot be interchanged in welding stainless steel. One such application is described in the example that follows.

Example 268. Change From Alternating to Direct Current for Welding Turbine Wheels When Material Was Changed From Alloy to Stainless Steel (Fig. 29)

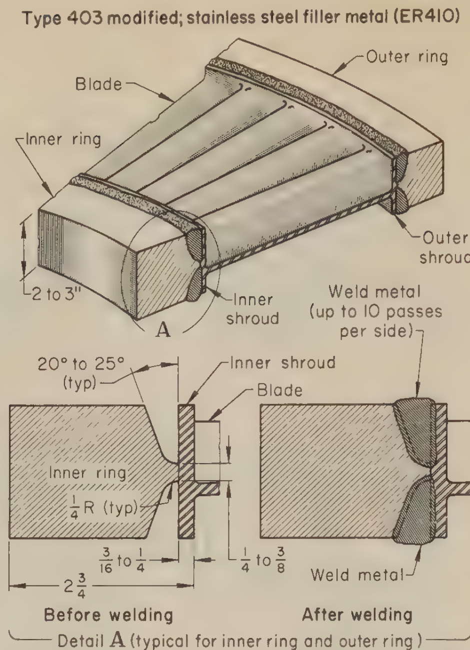
Turbine wheels of several sizes were fabricated by joining two rings to the inner and outer shrouds of the blade assembly by means of two double-J-groove welds, as shown in Fig. 29.

When low-alloy steel shrouds were joined to carbon steel rings, a neutral flux was used with a carbon steel electrode wire and alternating current. Distortion was minimized by control of the sequence of passes and the volume of weld metal deposited, and acceptable results were obtained.

Similar assemblies designed for higher-temperature service were made from a modified type 403 stainless steel and welded with ER410 electrode wire. This modified grade had a somewhat higher chromium content than standard 403 stainless steel. The welding conditions used for the low-alloy steel wheels were not satisfactory for welding the stainless steel wheels. The alternating-current arc was unstable and caused bridging to the sides of the groove without penetrating to the bottom, entrapping slag. Increasing the travel speed resulted in an irregular, ropey type of bead.

Two means of stabilizing the arc and thereby correcting the difficulty were considered: (*a*) widening the J-grooves by 25%, and (*b*) using direct current with reverse polarity. Because widening the J-grooves would require more filler metal, this change would increase distortion and add to the welding cost. Therefore, the change to reverse-polarity direct current was made.

Welding was done under the conditions listed with Fig. 29. Up to 20 passes were required for each joint. The first side was welded until a measurable amount of distortion was observed (usually after 3 to 5 passes); then the weldment was turned over and passes were made on the reverse side until distortion was observed; welding was alternated from side to side until the weldment was completed.



Process	Submerged-arc welding
Joint type	Circumferential butt
Weld type	Double-J-groove
Joint preparation	Machining
Power supply	Constant-voltage transformer-rectifier
Electrode wire	1/8-in.-diam ER410
Flux	Neutral
Welding position	Flat
Number of passes	10 to 20(a)
Current	450 to 500 amp, dcrp
Electrode stickout	1¼ to 1½ in.
Preheat	400 F min
Interpass temperature	400 F min
Postheat	Stress relieve at 1150 F(b)
Welding speed	15 ipm

(a) Passes made on alternate sides to minimize distortion. (b) For one hour per inch of thickness.

Fig. 29. Turbine wheel weldment (Example 268)

Electrode Wires (Filler Metals). Table 11 lists designations of electrode wires applicable to submerged-arc welding. Selection of filler metal for a particular grade of stainless steel is complicated by the differences in service requirements. If experience with a similar application is not available, use of a filler metal similar in composition to the base metal should be considered (see Examples 268 and 269). Adjustments (based on experience) may be required in the composition of the filler metal or the flux, or both, to arrive at a suitable composition of weld deposit. In some applications, a filler metal that is higher in alloy content than the base metal is used. For instance, the data with Fig. 28 show the use of ER308 filler metal for welding type 304 stainless steel.

Table 14. Relation of Wire Diameter to Current for Submerged-Arc Welding of Stainless Steel

Wire diameter, in.	Current range, amp	Wire diameter, in.	Current range, amp
3/32	120- 700	3/16	400-1300
1/8	220-1100	1/4	600-1600
5/32	340-1200	5/16	1000-2500

SOURCE: Same as Table 4

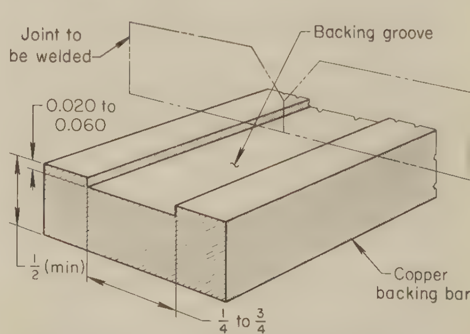


Fig. 30. Recommended groove dimensions for copper backing bars used in submerged-arc welding of stainless steel

Typical electrode wire size and current combinations are given in Table 14. Sizes larger than 3/16-in. diameter are seldom used, and may result in heavy deposits with undesirable metallurgical and mechanical properties.

Flux. Submerged-arc fluxes (either prefused or bonded) are available as proprietary materials for welding stainless steel. Alloying elements such as chromium, nickel, molybdenum and columbium are frequently added to the weld deposit through the flux. If the flux contains no alloying additions, it is said to be "neutral".

Weld Backing. Submerged-arc welding deposits relatively large volumes of metal that remain fluid for longer periods than are possible with the other arc methods discussed in this article. Thus, for many types of joints, backing is required.

The two common types of weld backing are nonfusible and fusible. Copper is the nonfusible backing material most frequently used in the welding of stainless steel. In effect, the copper bar serves more as a chill than as a backing, helping to distribute heat from the weld metal to adjacent areas. Recommended dimensions for grooves in copper backing bars are given in Fig. 30; many designs other than that shown in Fig. 30 are also used. With a fusible backing, made of stainless steel, the weld penetrates and fuses with the backing, which becomes, temporarily or permanently, an integral part of the welded joint (see Example 269).

Joint Design. Sound single-pass welds can be made in square-groove butt joints up to 5/16 in. thick, without root opening and with suitable nonfusible backing. Two-pass welds (one pass on each side) are made without root opening on metal up to 5/8 in. thick, but it is essential that the edges of the joint be closely butted to avoid burn-through, since weld backing is not used. A square-groove butt joint requires a minimum of edge preparation and produces sound welds that have adequate penetration.

Single-V-groove welds with a root face are used with nonfusible backing for single-pass butt joints of 5/16-in. thickness or more. For most applications, the maximum thickness of single-V-groove welds is 1¼ to 1½ in., with root-face dimensions 1/8 to 3/16 in. This joint design can be used for multiple-pass welds, without backing, where plate thickness exceeds 5/8 in. The first pass is made in the shallower V; the work is then turned over and welded on the reverse side. The root face is about 3/8 in. for multiple-pass welds.

The double-V-groove butt joint is the basic design for submerged-arc welding of material having a thickness of ½ in. or greater. A large root face is generally used. Figure 28 shows a typical double-V-groove weld in ½-in. type 304 plate. Welding conditions are included in the table with Fig. 28. A single-U-groove butt joint is also commonly used. Shielded metal-arc welding is often used to make a root pass, or backing pass, on the reverse side of the joint.

Welding Position. Submerged-arc welding is done in the flat or horizontal position. Operation difficulties in-

crease and preferred shape of beads is sacrificed when the work is inclined. Typical effects of inclination of the joint on formation of bead shape are compared in Fig. 31.

Welding Technique. The most common method of starting the arc when welding stainless steel is the fuse-ball start. A tightly rolled ball of stainless steel wool, about ⅜ in. in diameter, is placed between the end of the electrode and the work. The electrode wire is inched forward to compress the ball. Flux is added and the arc is initiated and flashes through the stainless steel wool. For details on other methods of starting the arc, see the article on Submerged-Arc Welding, which begins on page 46 in this volume.

Once the arc is started, welding conditions must be carefully monitored. The most important are current, voltage and travel speed. If current is too high, likely results are burn-through, pear-shape fusion zones, excessive penetration, and overlap or excessively high reinforcement. If current is too low, inadequate penetration and low reinforcement will result. When voltage is too high, the most common results are shallow penetration and wide reinforcement. Low voltage results in pear-shape fusion zones and narrow and steep-side reinforcement, or overlapped reinforcement. When welding speed is too high, undercutting and low reinforcement are likely results; too low a speed leads to overlap.

Circumferential Welding. Submerged-arc welding is used extensively for making girth welds for joining pipe or other cylindrical sections. Equipment required is generally the same as for welding cylindrical workpieces of carbon steel and is described in the article on Submerged-Arc Welding, which begins on page 46 in this volume.

In the application of submerged-arc welding to stainless steel pipe joints, some difficulty may be encountered in cleaning the root of the joint and in obtaining a sound weld root inside the pipe. These problems can be overcome by: (*a*) using a backing ring and making the root pass by shielded metal-arc welding, followed by submerged-arc welding for the filler passes; or (*b*) making the root pass by gas tungsten-arc welding, without backing, and completing the joint by submerged-arc welding. The example that follows describes the first of these alternatives.

Example 269. Use of a Stainless Steel Backing Ring in Welding Type 347 Stainless Steel Pipe Joints (Fig. 32)

Service conditions required the joint between type 347 stainless steel pipe sections, shown in Fig. 32, to be made with full penetration but without weld metal on the inside of the pipe. The groove was prepared by gas tungsten-arc cutting, with the pipe sections in position on turning rolls. Oxide on the surface was removed mechanically, and the pipe sections were assembled, with a stainless steel backing ring, to form the joint. The root pass was made by shielded metal-arc welding, and the weld was cleaned with a stainless steel brush and inspected visually. Visible flaws were removed by grinding.

Welding was completed in five additional passes by the submerged-arc process, under the conditions shown with Fig. 32, which were selected so as to avoid undercutting on the sidewalls of the weld groove. After each bead had been deposited, slag was removed by wire brushing, and any cracks and porosity were removed by chipping and grinding. Because of the susceptibility of the bead to cracking, the arc could not be struck on the weld bead already deposited and so it was struck on the side of the weld groove, and the stops and starts were subsequently ground out.

After completion of the joint, the fused flux was removed by brushing and the joint was prepared for radiographic inspection. Rejection rate was less than 5%.

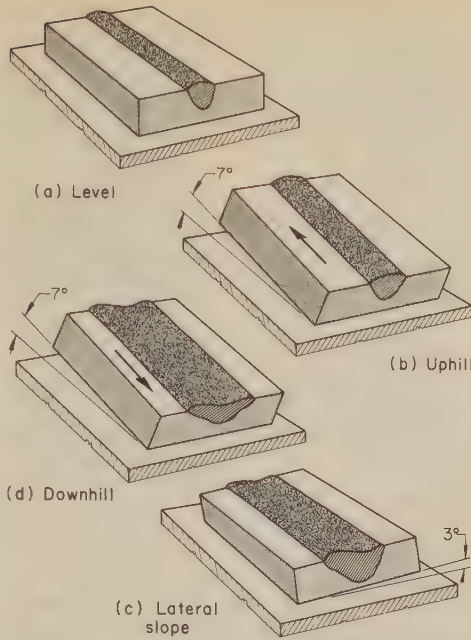
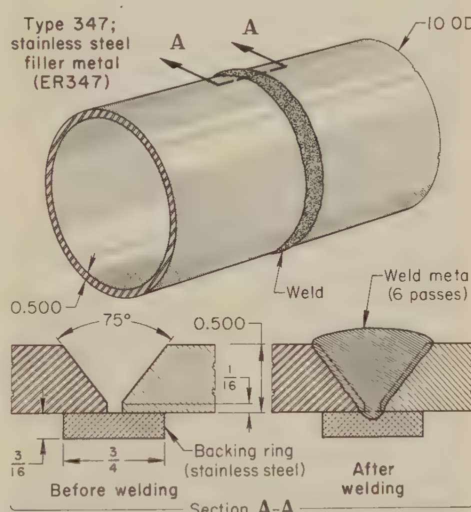


Fig. 31. Effect of work inclination on formation of bead shape in submerged-arc welding of stainless steel



Process	Submerged-arc welding(a)
Joint type	Butt
Weld type	Single-V-groove
Welding position	Horizontal-rolled pipe
Welding head	Fixed position, single wire
Number of passes	Six(a)
Preheat	None
Interpass temperature	400 F max
Postheat	None
Electrode wire	⅛-in.-diam ER347
Flux	Neutral
Current	240 to 260 amp, dcrp(b)
Voltage	25 v
Welding speed	12 to 15 ipm

(a) First pass made by shielded metal-arc welding. (b) Actual reading at welding head.

Fig. 32. Joint design and welding details for welding pipe sections, featuring the use of a stainless steel backing ring (Example 269)

Welding of Dissimilar Alloys

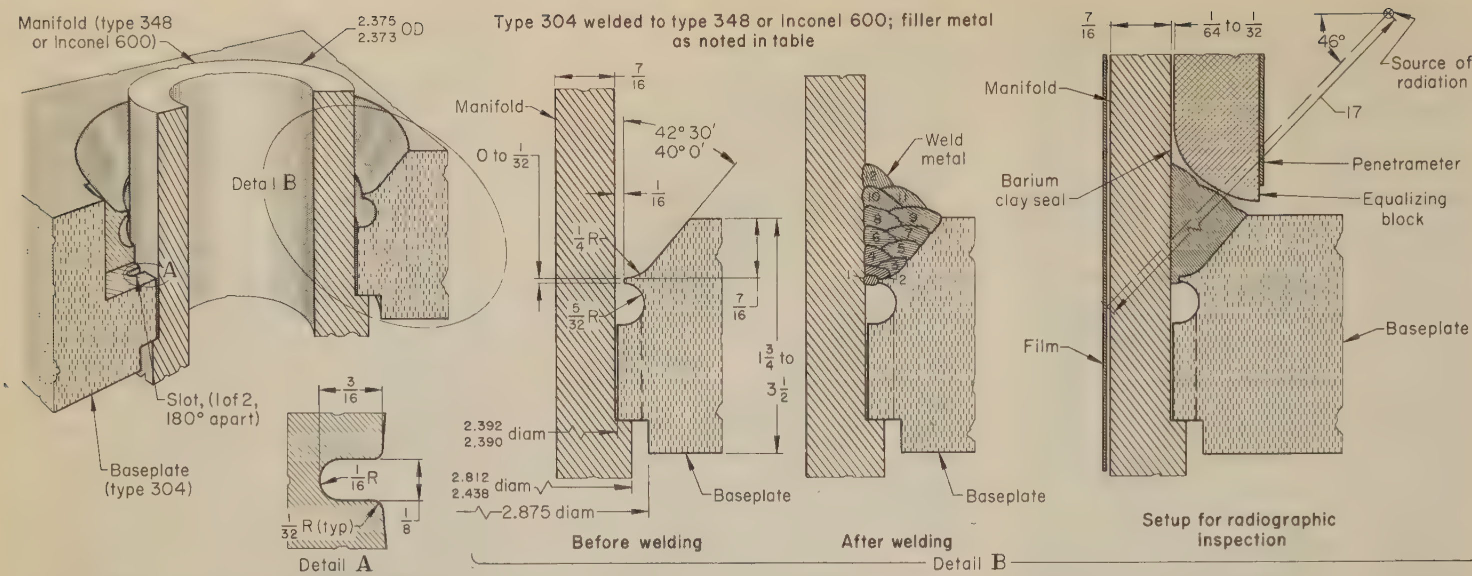
The welding of dissimilar austenitic stainless steels to each other is fairly common practice. When suitable welding procedures and filler metals are employed, most austenitic stainless steels can also be welded satisfactorily to several different classes of weldable steel, including ferritic and precipitation-hardening stainless steels, carbon steels, and low-alloy steels. The following examples in this article describe the welding of dissimilar austenitic or precipitation-hardening stainless steels, or of austenitic stainless steels to weldable carbon steels: Example 259 (316L to 17-7 PH); Example 260 (321 to low-carbon steel); Example 261 (AM-350 to 301); Example 262 (305 to 347); Example 264 (303 to 1020 low-carbon steel); Example 265 (321 to 347); and Example 270 (304 to 348 or Inconel 600). Example 251 in this article illustrates the use of spot welding to tack a ferritic stainless steel sheath to a carbon steel stiffener.

Dissimilar Austenitic Alloys. To accommodate varying requirements in service, it is not uncommon to weld different austenitic stainless steels, such as types 304 and 347, to each other or to a nickel-base alloy, using a filler metal that differs in chemical composition from both base metals. Recommended filler metals for welding dissimilar austenitic stainless steels are given in Table 8. In some applications, such as that described in Example 261, a precipitation-hardening stainless steel is welded to a conventional austenitic stainless steel. In the example that follows, welded components were made either of two different austenitic stainless steels or of an austenitic stainless steel and a nickel-base alloy.

Example 270. Welding Dissimilar Austenitic Alloy Components for a Nuclear Application (Fig. 33)

A sectional view of the manifold and baseplate assembly of a heat exchanger used in a nuclear application is shown at the extreme left in Fig. 33. Specifications required the use of manual gas tungsten-arc welding for the root pass and second pass of the joint between the baseplate (made of type 304 stainless steel) and the manifold (made of either type 348 stainless steel or Inconel 600). The remaining passes could be made by either gas tungsten-arc or shielded metal-arc welding. In this example, all weld metal was deposited by gas tungsten-arc welding.

Before welding, the joint edges of the baseplate and manifold were machined to the dimensions shown in Fig. 33 (detail B, Before welding). The joint and adjacent base metal (for a distance of 2 in.) were cleaned free of oil, scale, oxide, and other contaminants. Welding-grade argon was used for shielding and purging during welding, and purging-gas flow was continued until all metal surfaces had cooled to 300 F. The root pass and second pass were made by depositing small (as small as possible) stringer beads that merged uniformly with the base metal. After deposition, each weld was cleaned thoroughly and inspected visually at a magnification of not less than 5×. Cracked welds were removed completely and rewelded. After each subsequent pass, the weld beads were cleaned with a stainless steel brush or an aluminum oxide grinding disk not previously used on other kinds of metals.



Process	Manual gas tungsten-arc welding
Joint type	Circumferential T
Weld type	Single-J groove(a)
Power supply	600 amp
Shielding gas	Argon, at 10 to 15 cfh
Arc starting	Manual
Electrode:	
Root pass and 2nd pass	1/16-in.-diam
Subsequent passes	3/32-in.-diam
Filler metal:	
Root pass and 2nd pass	1/16-in.-diam, ER308(b) or FM82(c)
Subsequent passes	3/32-in.-diam, ER308(b) or FM82(c)
Current (dcsp):	
Root pass and 2nd pass	110 to 120 amp
Subsequent passes	110 to 130 amp
Voltage	12 to 14 v
Preheat and postheat	None(d)
Interpass temperature	300 F (max)
Welding speed	12 to 18 ipm

(a) Fillet reinforced. (b) For joining type 304 to type 348 steel. (c) For joining type 304 to Inconel 600 (0.10 C, 67 Ni, 20 Cr, 2.5 Cb). (d) Work metal heated to 60 F if temperature before welding was below 60 F.

Fig. 33. Joint design, weld pass sequence and setup for radiographic inspection of finished weld of manifold and baseplate assembly for a nuclear application (Example 270)

The minimum allowable base-metal temperature at the start of welding was 60 F, and the maximum interpass temperature was 300 F. No postweld heat treatment was required. Other welding conditions are given in the table that accompanies Fig. 33.

A pedal for controlling amperage at starts and stops of the weld passes was used to control heat buildup and to minimize crater cracks. Procedures and welders were qualified in accordance with nuclear standards. In addition to visual inspection, the root and final passes were inspected by the liquid-penetrant method and the completed weld was inspected radiographically. To equalize the intensity of the x-rays across the entire width of the weld, a contoured, 3/8-in.-thick equalizing block (corresponding to the alloy used in the vertical member of the weldment) was placed, as shown at the extreme right in Fig. 33, at a distance of 1/64 to 1/32 in. from the vertical member and separated from the vertical member and weld by a layer of barium clay. Verification radiographs of the weld were made with a penetrameter in place.

Welding Austenitic Stainless Steel to Carbon or Low-Alloy Steel. In joining austenitic stainless steel to carbon or low-alloy steel for service applications involving exposure to temperatures not exceeding about 700 F, it is good practice to use a stainless steel filler metal of total alloy content high enough to prevent martensite formation in the weld after dilution by the opposing base metal and to preserve residual amounts of ferrite to minimize the possibility of hot cracking resulting from welding under severe restraint. Type 309 (25Cr-12Ni) filler metal is most widely used for joining carbon or low-alloy steel to austenitic stainless steel; it normally contains about 5 to 10% ferrite. Type 312 (29Cr-9Ni), also used for this purpose, is more strongly ferritic. Satisfactory welds are also obtained with ERNiCrFe-6 filler metal.

In joining austenitic stainless steel to carbon steel, it is good practice first to surface (butter) the carbon steel with a layer of type 309 or other suitable stainless steel weld metal, so that the portion of the weld (on the carbon steel member) where difficulties are most likely to occur is deposited while there is little restraint on the weld metal. Thus, following deposition and inspection of the surfacing layer (or layers), the joint between the stainless steel member and the surfaced layer becomes a stainless-steel-to-stainless-steel joint, which can be welded by using a conventional stainless steel filler metal.

The deposition of carbon steel or low-alloy steel filler metal on austenitic stainless steel should be avoided whenever possible because it can result in hard, brittle weld deposits.

A procedure for joining stainless steel to carbon steel or to stainless-clad carbon steel is shown in Fig. 34. This procedure is widely used in the welding of stainless steel pipe to stainless-clad carbon steel, low-alloy steel, and carbon steel.

In depositing the surface layer, dilution of the stainless steel weld metal by carbon steel, which can cause cracking of the weld, can be minimized with the following practices. If the cladding on stainless-clad steel is type 304 stainless steel, type 309 should be used for the surfacing layer. After depositing the surfacing layer, the component is stress relieved, if necessary. The final weld between the solid stainless steel and the surfaced stainless-clad steel or carbon steel can be made either with the filler metal normally employed for welding the solid stainless steel member or with the one that was used for the overlay.

In another method, a short stainless steel transition member is welded to the carbon steel or stainless-clad carbon steel member prior to stress relieving and final welding. This method ensures protection of the carbon steel base metal from the effect of final welding, and stress relieving can be done while there is little restraint on the joint. This method, however, is more costly than the procedure for producing a surfacing layer.

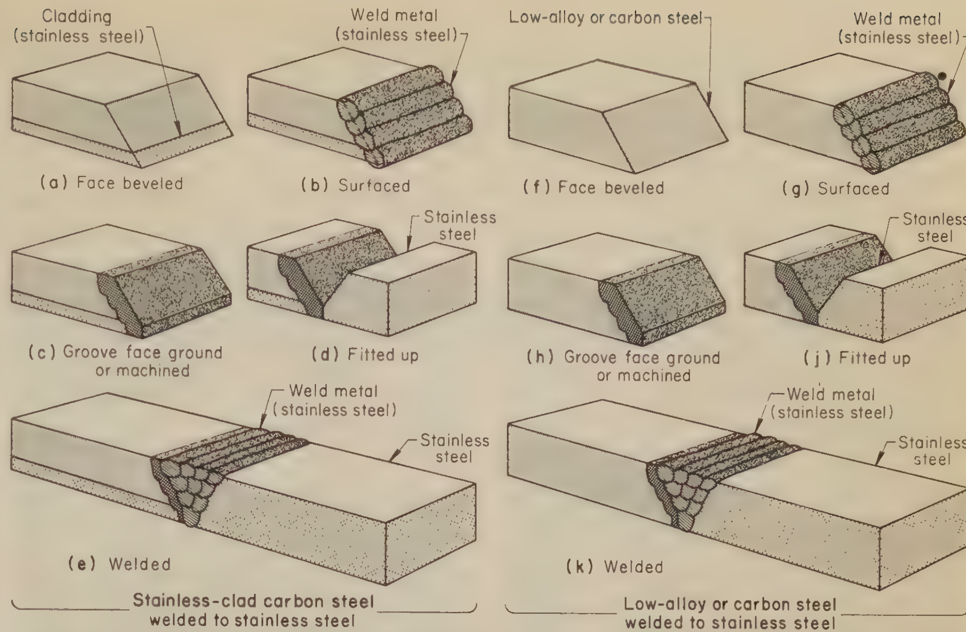
In a third method, the workpieces (stainless steel and carbon steel or stainless-clad carbon steel) are beveled and fitted, leaving a root opening at the joint that is then welded with a filler metal of sufficiently high alloy content to prevent cracking of the weld after dilution by carbon steel. The welding procedure should be controlled to hold penetration into the surface of the carbon steel to a minimum. A disadvantage of this method is that the joint is under restraint both during welding and local stress relieving. This method, although often used, is the least desirable of the three.

Welding Ferritic and Martensitic Stainless to Carbon and Low-Alloy Steel. When welding ferritic or martensitic stainless steel to carbon or low-alloy steel for general service (not high-temperature service), the use of austenitic stainless steel or modified ERNiCrFe-6 filler metal can produce welds of suitable quality if correct welding procedures are followed.

Two methods are commonly employed. The first method involves surfacing both members of the joint, using suitable preheat and postheat treatments as required, and then making a weld between the buttered surfaces without preheat or postheat. Filler metals, such as type 309, that are sufficiently high in alloy content to minimize dilution by carbon steel or straight-chromium stainless steel are widely used with this method. Penetra-

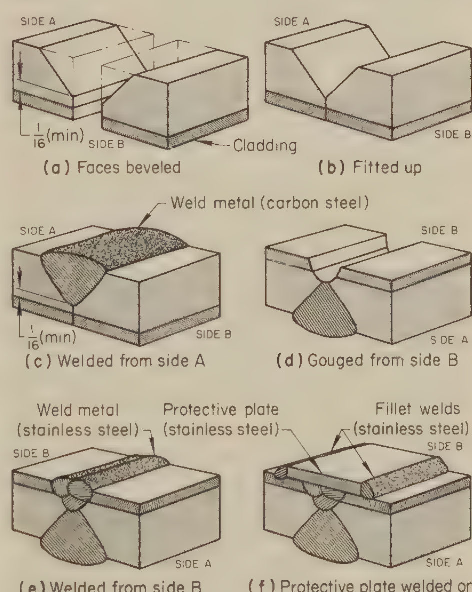
tion into the base metal should be kept to a minimum.

The second method involves depositing the filler metal directly on the surfaces of the two members of the joint without using a separate surfacing layer. Dilution of the weld metal by both base metals must be kept under close control while the restrained joint is being welded.



Stainless-clad, low-alloy or carbon steel edges are beveled for welding (a and f); an overlay (or "buttering" layer) of stainless steel filler metal is applied to the beveled edge (b and g); the layer is machined or ground to required dimensions and stress relieved, if required (c and h); the components are fitted up for welding (d and j); the weld is completed, using the filler metal normally used for welding the stainless steel member or that used for the surfacing pass on stainless-clad, low-alloy or carbon steel (e and k).

Fig. 34. Procedures for joining austenitic stainless steel to stainless-clad carbon steel, solid carbon steel, and low-alloy steel



(a and b) The clad plates are machined for a tight fit-up, with the bottom of the weld groove not less than $\frac{1}{16}$ in. above the stainless steel cladding; (c) carbon steel filler metal is deposited from side A (a low-hydrogen filler metal is used for the first pass), taking care not to penetrate closer than $\frac{1}{16}$ in. to the cladding; (d) stainless steel cladding on side B is back gouged until sound carbon steel weld metal is reached; (e) the back-gouged groove is filled with stainless steel weld metal in a minimum of two layers. (f) When required for severely corrosive service, a protective strip of stainless steel plate may be fillet welded to the cladding to cover the weld zone.

Fig. 35. Procedure for welding stainless-clad carbon and low-alloy steel, using stainless steel filler metal only in portion of joint from which cladding was removed

Welding Austenitic-Stainless-Clad Carbon or Low-Alloy Steel Plate

To preserve its desirable properties, stainless-clad plate can be welded by either of the two following methods, depending on plate thickness and service conditions:

1 The unclad sides of the plate sections are beveled and welded with carbon or low-alloy steel filler metal. A portion of the stainless steel cladding is removed from the back of the joint and stainless steel filler metal is deposited.
2 The entire thickness of the stainless-clad plate is welded with stainless steel filler metal.

When the nonstainless portion of the plate is comparatively thick, as in most pressure-vessel applications, it is more economical to use the first method. When the nonstainless portion of the plate is thin, the second method is often preferred. When welding components for applications involving elevated or cyclic temperatures, the differences in the coefficients of expansion of the base plate and the weld should be taken into consideration.

All stainless steel deposits on carbon steel should be made with filler metal of sufficiently high alloy content to ensure that normal amounts of dilution by carbon steel will not result in a brittle weld. In general, filler metal of type 308, 316 or 347 should not be deposited directly on carbon or low-alloy steel. Deposits of type 309, 310 or 312 are usually acceptable, although type 310 is fully austenitic and is susceptible to hot cracking when there is high restraint in a welded joint. Thus, welds made with type 310 filler metal should be carefully inspected. Welds made with types 309 and 312 filler metals are partially ferritic and therefore are highly resistant to hot cracking.

The procedure most commonly used for making welded joints in stainless-clad carbon or low-alloy steel plate is shown in Fig. 35. Stainless steel filler metal is deposited only in that portion of the weld where the stainless steel cladding has been removed, and carbon or low-alloy steel filler metal is used for the remainder.

The back-gouged portion of the stainless steel cladding should be filled with a minimum of two layers of stainless steel filler metal (Fig. 35e); an additional layer is recommended if a high weld reinforcement at the cladding surface can be tolerated.

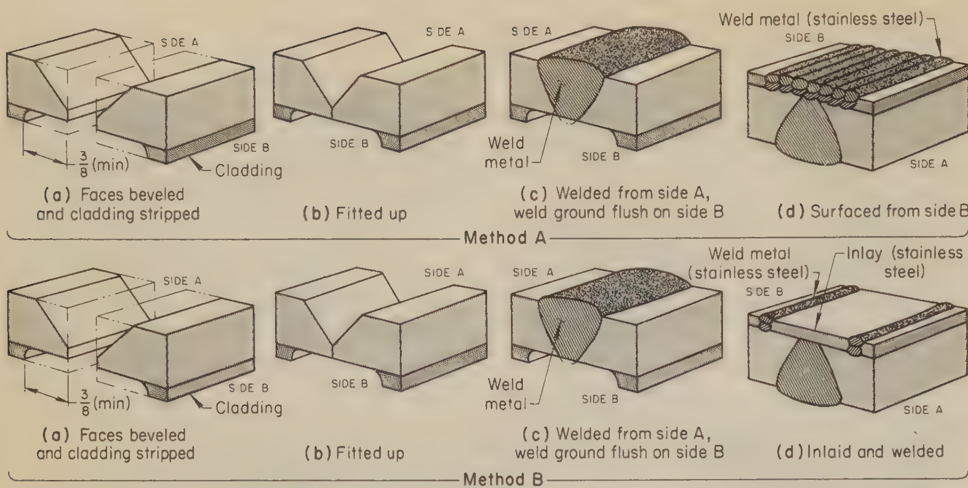
If the cladding is of type 304 stainless steel, the first layer of stainless steel weld metal should be of type 309 or 312. Subsequent layers of weld metal can be of type 308.

If the cladding is of type 316, the first layer is deposited with type 309(Mo) filler metal and the subsequent layers with type 316. Alloy 20 (20 Cr, 29 Ni, 2 Mo, 3 Cu, 0.07 C) filler metal is also frequently used on plate clad with type 316. When the cladding is of type 304L or type 347, the welding procedure must be carefully controlled to obtain the desired weld-metal composition in the outer layers of the weld. Chemical analysis of sample welds should be made before joining of clad plates intended for use under severely corrosive conditions.

In some applications, a narrow protective plate of wrought stainless steel of the same composition as the cladding is welded over the completed weld (Fig. 35f) to ensure uniformity of corrosion resistance. The fillet welds joining the protective plate to the cladding should be carefully inspected after deposition. These welds, of course, are made with stainless steel filler metal.

Figure 36 illustrates an alternative method (method A) of welding clad plate in which a carbon or low-alloy steel weld joins the carbon steel portion of the plate and the use of stainless steel filler metal is limited to replacement of the cladding that was removed prior to making the carbon or low-alloy steel weld. This method is more expensive than the previous one (Fig. 35), because of the cost of removing a larger portion of the cladding and depositing more stainless steel filler metal. Because there is no danger of alloy contamination from the cladding layer, method A in Fig. 36 permits the use of faster welding processes, such as submerged-arc, in depositing the carbon steel weld.

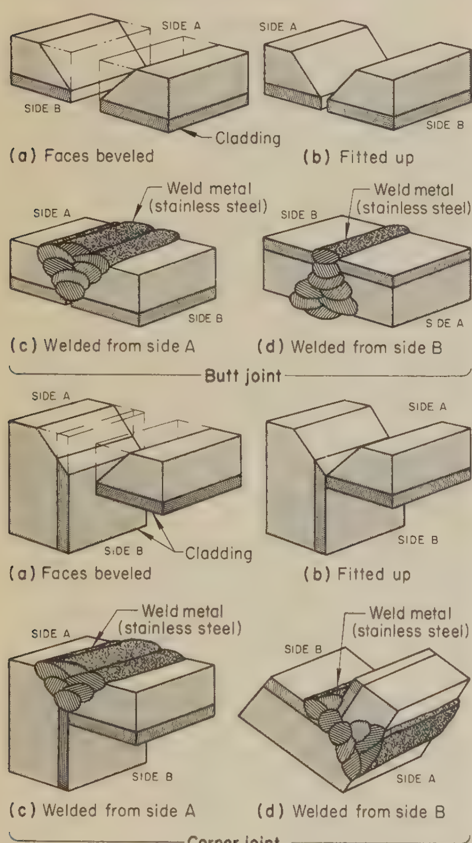
In depositing the stainless steel weld metal, the first layer must be sufficiently high in alloy content to avoid cracking as a result of normal dilution by the carbon steel base metal. A stringer-bead technique should be employed, taking care to hold penetration to a minimum. If the proper weld-metal composition is not achieved after the second layer has been deposited, a



The joint is prepared by beveling side A and removing a portion of the stainless steel cladding from side B to a minimum width of ⅜ in. from each side of the joint, and the joint is fitted up in position for welding; use of a root gap (not shown) is permissible (a and b, methods A and B); carbon steel filler metal is deposited and the root of the weld is ground flush with the underside of the carbon steel plate (c, methods A and B); the area from which cladding was removed is surfaced with at least two layers of stainless steel weld metal (d, method A), or an inlay of wrought stainless steel can be welded in place (d, method B).

Fig. 36. Alternative procedures for joining stainless-clad carbon and low-alloy steel plate involving different techniques for replacing portions of the stainless steel cladding removed before welding the carbon or low-alloy steel side

portion of the second layer should be ground off and additional filler metal should be deposited to obtain the desired composition. Method B, Fig. 36(d), shows an alternative procedure in which the exposed carbon steel weld on side B is covered by welding an inlay of wrought stainless steel to the edges of the cladding.



The clad plates are beveled and fitted up (a and b, butt and corner joints); stainless steel filler metal is deposited from the carbon steel side (c, butt and corner joints); the root of the weld is cleaned and gouged, if necessary, before depositing stainless weld metal from the stainless steel side (d, butt and corner joints).

Fig. 37. Procedures for welding V-groove butt and corner joints in stainless-clad carbon or low-alloy steel plate, using stainless steel filler metal exclusively

The most common method of joining stainless-steel-clad carbon or low-alloy steel plate with a weld that consists entirely of stainless steel is shown in Fig. 37. This method is most frequently used for joining thin sections of stainless-clad plate.

The same basic welding procedure is followed for both the butt and corner joints shown in Fig. 37. After the plate has been beveled and fitted up for welding, a stainless steel weld is deposited from the carbon steel side, using a filler metal sufficiently high in alloy content to minimize difficulties (such as cracking) resulting from weld dilution and joint restraint. Types 309 and 312 filler metals are suitable for this application.

After the stainless steel weld has been deposited from the carbon steel side (Fig. 37c), the root of the weld is cleaned by brushing, chipping or grinding, as required, and one or more layers of stainless steel filler metal are deposited (Fig. 37d). The filler-metal composition should correspond to that normally employed to weld the type of stainless steel used for the cladding. If the cladding is type 304, the final layer of weld metal should be type 308. If the cladding is type 316, it may be necessary to back-gouge before deposition of the final weld-metal layers to ensure that the proper weld-metal composition is obtained at the surface of the weld.

Welding of Castings

Table 15 lists designations for 12 corrosion-resistant steel casting alloys covered by ASTM A296, and relates these alloys to the AISI types of wrought stainless steels that are approximately equivalent to the respective casting alloys in composition. From Table 15 it is evident that corrosion-resistant steel castings are produced in conventional austenitic, ferritic and martensitic grades, as well as in some special grades such as extra-low-carbon (CF-3) and columbium-stabilized (CF-8C).

Commercial uses for the casting alloys are closely related to the applications for their wrought counterparts; principally for service in corrosive environments at temperatures no higher than 1200 F. Valves, piping and vessels in chemical-processing plants are typical applications for welded corrosion-resistant steel castings, welded either to other castings (to produce composite castings) or to wrought components. A major field of application is welding for repair of defective castings in the foundry.

Welding Processes. All of the arc welding processes and electroslag welding are used for welding of corrosion-resistant steel castings. For information on the individual processes, see the articles on Shielded Metal-Arc Welding, Gas Metal-Arc Welding, and so on, in this volume.

For the repair of casting defects in the foundry, shielded metal-arc welding is most often used, largely because of its versatility. For welding to produce composite castings or to join sections of cast pipe, one of the arc processes capable of higher deposition rates, such as gas metal-arc or submerged-arc welding, is more often used. For joining large castings with relatively thick walls (generally, thicker than 1 in.), electroslag welding is often used because it costs less than arc welding for thick sections.

Welding Procedures. With other conditions being equal, whether a given part is wrought or cast has little or no effect on procedures and filler metals used for welding. (For instance, if a part of specific size and shape was made from type 410 stainless steel for which a welding procedure was established, changing to a CA-15 casting would not require a change of filler metal or procedure.) However, as-cast surfaces require more elaborate preparation for welding; foreign materials such as oxides and sand inclusions must be removed before as-cast surfaces can be satisfactorily welded.

Filler metals, joint design and operating conditions for welding wrought stainless steels, but also applicable to their cast counterparts, are given in Tables 1, 4, 5, 6, 7, 8, 9, 10, 12, 13 and 14 in this article.

The discussion in this article on causes and prevention of undesirable conditions, such as carbide precipitation in the welded joints of certain austenitic grades of wrought stainless steels, is generally applicable also to the corrosion-resistant steel castings.

Table 15. Some Corrosion-Resistant Steel Casting Alloys, and Wrought Stainless Steels of Approximately Equivalent Compositions

Casting alloy (ASTM A296)	Wrought alloy (AISI type)	Casting alloy (ASTM A296)	Wrought alloy (AISI type)
CA-15	410	CF-8C	347
CA-40	420	CF-8M	316
CB-30	431	CF-16F	303
CC-50	446	CF-20	302
CF-3	304L	CH-20	309
CF-8	304	CK-20	310

Arc Welding of Heat-Resisting Alloys

*By the ASM Committee on Welding of Heat-Resisting Alloys**

HEAT-RESISTING ALLOYS considered in this article include nickel-base alloys, iron-nickel-chromium and iron-chromium-nickel alloys, cobalt-base alloys, and refractory metals. The procedures used in welding heat-resisting alloys depend to some extent on the mechanism by which they are strengthened for high-temperature service — primarily solid-solution strengthening or precipitation hardening.

Many of the heat-resisting alloys are susceptible to cracking during welding or during subsequent heat treatment. The severe service conditions to which heat-resisting alloys are exposed make changes in microstructure and properties, as produced by arc welding, of special importance, and make avoidance of cracking imperative.

Nominal compositions of commonly arc welded heat-resisting alloys are given in Table 1.

Welding Processes. Heat-resisting alloys can be welded by all the arc welding processes. Gas tungsten-arc welding is widely used, especially for joining thin sections. In general, shielded metal-arc and gas metal-arc welding are used in joining sections more than 1 in. thick, where the heat input will not adversely affect the weld metal or the base metal. Submerged-arc welding is used to a lesser extent. Example 285 describes the use of submerged-arc welding in joining an Fe-Ni-Cr heat-resisting alloy to an alloy steel.

Argon is generally preferred as the shielding gas for arc welding of heat-resisting alloys because of its low cost and high density, and because of the arc stability and weld uniformity obtainable with it. Argon was used in most of the examples of gas-shielded arc welding described in this article. Helium, because of the higher heat input obtainable with it, is used in mixtures with argon, and alone, in welding thick sections. Small amounts of hydrogen, and less frequently of carbon dioxide, are sometimes added, as in Example 275.

Welding current is typically straight-polarity direct current (dcsp) for gas tungsten-arc welding and reverse-polarity direct current (dcrp) for gas metal-arc welding.

The data in Table 2 are intended to serve as starting points for the establishment of machine settings for gas tungsten-arc welding. These conditions are, in general, suitable for welding nickel-base, Fe-Ni-Cr, Fe-Cr-Ni and cobalt-base alloys, when making butt, corner or T-joints, using an appropriate groove design based on stock thickness and application. An increase in welding current of 10 to 20 amp may be needed for melt-through T-joints. Generally, the interpass temperature should be below 200 F. Oscillation of the welding torch may help to prevent cracking by changing the solidification pattern and may also improve the appearance of the weld.

Edge Preparation. Edges should be squared, aligned properly, and, if necessary, tack welded before welding. Misalignment and misfit cause variation in bead contour and root opening, and stresses in the weld area, which can cause cracking in the welded joint.

Machining is the best way to obtain a good-fitting bevel edge. When sheet or plate more than 0.090 in. thick is sheared, the sheared edge should be ground or machined back an additional 1/32 to 1/16 in., to remove stressed metal, before welding.

Cleaning of Workpieces

The weldability of heat-resisting alloys is markedly affected by the cleanness of the base metal and of the filler metal. Shop dirt (such as paint, grease, and oil), oxide film, and scale are the main surface contaminants. Sulfur and lead in foreign material on the workpiece surface can diffuse into the base metal when it is heated and can result in severe cracking.

Processes for the removal of surface dirt are described in Volume 2 of this Handbook. Grease and oil are removed by commercial solvents and by vapor degreasing. Soaps can be removed by rinsing in hot water. Soluble oils, tallow, fats and fatty acids require a more complex cleaning procedure.

Techniques for removal of tarnish, oxide films, and heavy scale are described in the articles on Cleaning and Finishing of Heat-Resisting Alloys and Cleaning and Finishing of Nickel and Nickel Alloys, beginning on pages 607 and 661, respectively, in Volume 2 of this Handbook.

Dust that has settled on the workpieces after cleaning can be removed by carefully wiping the joint area with clean, lint-free cloths dampened with a solvent such as methyl ethyl ketone. In order to avoid surface contamination of cleaned workpieces, white gloves are used during handling. In some of the examples in this article, carbon tetrachloride was used to wipe the joint area after machining. This should be done only in a well-ventilated shop, because the fumes are highly toxic. In some states, the use of carbon tetrachloride is prohibited.

After welding, all slag must be removed. If slag left on a weldment should become molten during service, severe attack on the metal may occur. With multiple-pass welding, slag must be removed between passes; sometimes, grinding of the weld bead is needed.

Welding Fixtures

Fixtures used in arc welding heat-resisting alloys are generally similar to those used in a similar applications on other metals. Chill bars are often used to cool the weld area rapidly. Backing bars, inserts and facing plates that are in contact with the workpieces on either the root or the face side of the welds should be located so as not to contaminate the weld metal or base metal. These accessories are usually made of copper.

Hold-down bars and backing bars extend the full length of the weld. The backing bars usually contain passages to facilitate inert gas shielding. When grooved backing bars are used, the grooves should be shallow to minimize melt-through and to limit the height of the root reinforcement. Grooves in backing bars should have rounded corners or be elliptical in shape to prevent entrapment of slag.

In the following example, a fixture was used to locate and clamp each piece during tack welding and to provide firm support during the final welding pass.

Example 271. Use of a Shaped Backing Fixture and Clamps To Provide Alignment in Gas Tungsten-Arc Welding of Two Formed Rings (Fig. 1)

Two formed rings were circumferentially butt welded to form an air seal for a compressor stage, as shown in Fig. 1. The thickness of each ring varied, but it was 0.040 in. on each ring at the weld joint.

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C. E. GUMBERT, Vice President, Vac-Hyd Processing Corp.; JAMES B. HUGHES, Welding Engineer, Materials Research and Process Engineering, Douglas Aircraft Co., Inc.; HENRY JAMES, Technical Assistant to the President, Sciaky Bros., Inc.; K. C. LOWSTETTER, Technical Director, Engineered Products Div., Abex Corp.; FORBES M. MILLER, Director, Brazing Engineering Center, Wall Colmonoy Corp.; K. J. MILLER, Development Engineer, Technical Center, Caterpillar Tractor Co.

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Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees.

The welding procedure described below was that used for completing Waspaloy rings; rings made of Inconel alloys were also assembled by welding.

The fixture and method of clamping the rings for welding are shown in Fig. 1, detail A. The groove in the backing fixture provided a passageway for the backing gas, which was fed into the groove through a series of small holes, to ensure its being distributed evenly.

The rings were in the solution-treated condition when welded. Surface oxides were removed for a minimum of ½ in. from the joint edges by a 240-grit aluminum oxide wheel mounted on an air grinder, followed by wiping with carbon tetrachloride. The cleaned rings were assembled in the fixture, as shown in Fig. 1, detail A, making certain that the joint line was centered over the backing groove and that joint alignment was within 0.005 in. as determined by dial-indicator measurement. The backing groove was purged with shielding gas before welding began.

The rings were tack welded by the manual gas tungsten-arc process, using 24 welds ⅜ in. long, equally spaced along the joint. A penetration of 0.010 to 0.015 in. was required. After tack welding, the rings were welded in one pass by the automatic gas tungsten-arc process, using high-frequency arc starting, Waspaloy filler metal, and gas shielding from the torch and a trailing shield, and through the backing fixture. After the weld was made, wire feed was stopped and the current was decreased slowly. Shielding-gas flow was maintained until after the weld metal solidified.

The welded assembly was heat treated at 1600 F for 1 hr and at 1400 F for 10 hr. Before and after heat treatment, welds were inspected for surface cracks by fluorescent-penetrant techniques, and for internal cracks by x-ray radiography.

Details of the welding operation are given in the table that accompanies Fig. 1.

In the example that follows, a welding positioner with a table that could be rotated 360° and tilted from a horizontal to a vertical position permitted welding in the flat, or nearly flat, position and rotation of the workpiece.

Example 272. Use of a Tilting, Rotating Welding Positioner for Making Circumferential Welds (Fig. 2)

A 1/16-in.-thick inner band was welded to a ¼-in.-thick section of the outer case of a Waspaloy turbine-shroud ring, as shown in Fig. 2. Two corner-joint welds were made automatically in two passes each, using a fixture that was mounted on the table of a welding positioner. The outer case was clamped to a backing ring and the inner band was held against the outer case by expanding jaws while the first weld was being made (detail B in Fig. 2). The expanding jaws were removed to provide access for the second weld. The workpiece and torch were positioned for each weld as shown in Fig. 2. The welding positioner continuously rotated the workpiece under the torch, which was stationary.

Gas tungsten-arc welding was used. The initial pass for each weld was made without filler metal, and the second pass was made with a 0.032-in.-diam Waspaloy filler-metal wire. The assembly was purged with argon for 5 min before beginning each weld, and argon shielding gas was used at the torch for all passes. Details for making the two welds are summarized in the table that accompanies Fig. 2.

The parts were welded in the solution-treated condition. Welded assemblies were heat treated at 1600 F for 1 hr and at 1400 F for 10 hr.

The J-grooves were machined, and then the grooves and the surfaces adjacent to the weld area on both components were wiped with methyl ethyl ketone. White gloves were used for handling the workpieces after cleaning.

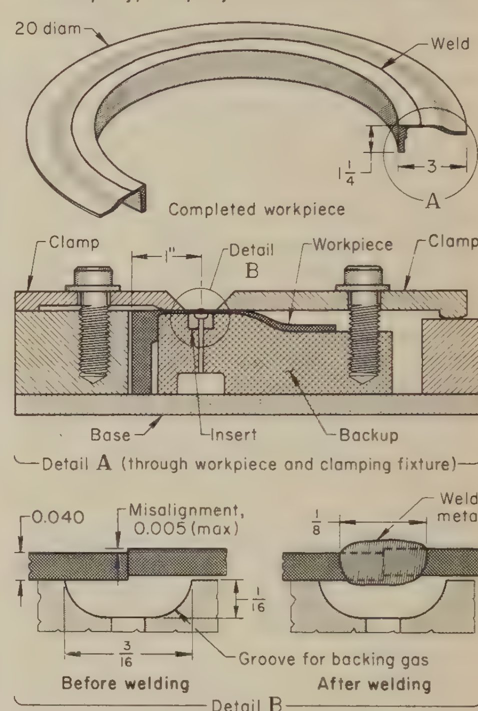
In order to obtain reproducible results, electronic governor controls were used to maintain the proper welding speed and wire-feed rate.

Welding chambers can be used for welding complex assemblies that would be difficult to fixture and protect properly in air. However, unless the chamber is properly designed and constructed, the inert gas in it is likely to be of much poorer quality, and less effective in shielding the work metal, than the inert gas contained in the conventional flowing shields, because of leakage of air and water vapor.

Table 1. Nominal Composition of Heat-Resisting Alloys

Alloy	Composition
Solid-Solution Nickel-Base Alloys	
Hastelloy B	0.05 C, 28 Mo, 5 Fe, 0.4 V, rem Ni
Hastelloy C	0.08 C, 15 Cr, 16 Mo, 6 Fe, 5 W, rem Ni
Hastelloy C276	0.02 C, 15 Cr, 16 Mo, 6 Fe, 4 W, rem Ni
Hastelloy N	0.04 C, 7 Cr, 16.5 Mo, 5 Fe, 0.5 Co, 0.01 B, rem Ni
Hastelloy X	0.08 C, 22 Cr, 9 Mo, 18.5 Fe, 1.5 Co, 0.6 W, rem Ni
Inconel 600	0.04 C, 76.0 Ni, 16 Cr, 7 Fe
Inconel 601	0.05 C, 60.5 Ni, 23 Cr, 14 Fe, 1.35 Al
Inconel 625	0.05 C, 61.0 Ni, 22 Cr, 9 Mo, 3 Fe, 0.2 Al, 0.2 Ti, 4 Cb
Precipitation-Hardenable Nickel-Base Alloys	
GMR-235	0.15 C, 15.5 Cr, 5.25 Mo, 10 Fe, 3 Al, 2 Ti, 0.06 B, rem Ni
Inconel 700	0.12 C, 46.0 Ni, 15 Cr, 3.7 Mo, 0.7 Fe, 28.5 Co, 3 Al, 2.2 Ti
Inconel 702	0.04 C, 79.5 Ni, 15.5 Cr, 0.4 Fe, 3.4 Al, 0.7 Ti
Inconel 706	0.03 C, 41.5 Ni, 16 Cr, 40 Fe, 0.2 Al, 1.75 Ti, 2.9 Cb
Alloy 713C	0.12 C, 12.5 Cr, 4.2 Mo, 6 Al, 0.8 Ti, 2 Cb, 0.10 Zr, 0.012 B, rem Ni
Alloy 718	0.04 C, 52.5 Ni, 18.5 Cr, 3 Mo, 18.5 Fe, 0.4 Al, 0.9 Ti, 5 Cb
Inconel 722	0.04 C, 75.0 Ni, 15.5 Cr, 7 Fe, 0.7 Al, 2.5 Ti
Inconel X-750	0.04 C, 73.0 Ni, 15 Cr, 7 Fe, 0.8 Al, 2.5 Ti, 0.9 Cb
M-252	0.15 C, 19 Cr, 10 Mo, 10 Co, 1 Al, 2.6 Ti, 0.09 Zr, 0.005 B, rem Ni
René 41	0.09 C, 19 Cr, 10 Mo, 11 Co, 1.5 Al, 3.1 Ti, 0.005 B, rem Ni
Udimet 700	0.08 C, 15 Cr, 5.2 Mo, 18.5 Co, 4.3 Al, 3.5 Ti, 0.030 B, rem Ni
Waspaloy	0.07 C, 19.5 Cr, 4.3 Mo, 13.5 Co, 1.4 Al, 3.0 Ti, 0.09 Zn, 0.006 B, rem Ni
Iron-Nickel-Chromium and Iron-Chromium-Nickel Alloys	
16-25-6	0.08 C, 16 Cr, 25 Ni, 6 Mo
17-14 CuMo	0.12 C, 17 Cr, 14 Ni, 3 Cu, 2.5 Mo, 0.25 Ti, 0.45 Cb
19-9 DL	0.3 C, 19 Cr, 9 Ni, 1.25 Mo, 1.20 W, 0.3 Ti, 0.4 Cb
A-286	0.05 C, 26 Ni, 15 Cr, 1.3 Mo, 0.2 Al, 2.0 Ti, 0.003 B
Discaloy	0.04 C, 25 Ni, 13.5 Cr, 2.7 Mo, 0.1 Al, 1.7 Ti, 0.005 B
Incoloy 800	0.04 C, 32 Ni, 20 Cr, 46 Fe
Incoloy 801	0.04 C, 32 Ni, 20 Cr, 46 Fe, 1 Ti
Incoloy 802	0.35 C, 32.5 Ni, 21 Cr, 46 Fe, 0.58 Al, 0.75 Ti
Incoloy 901	0.05 C, 43 Ni, 13.5 Cr, 34 Fe, 6.2 Mo, 0.25 Al, 2.5 Ti
N-155	0.15 C, 20 Ni, 21 Cr, 3 Mo, 20 Co, 1 Cb + Ta, 2.5 W, 0.15 N
Thermalloy 40B	0.32 C, 13 Ni, 25 Cr
Cobalt-Base Alloys	
HS-21	0.25 C, 3 Ni, 27 Cr, 5 Mo, 1 Fe, 62 Co
HS-25 (L-605)	0.10 C, 10 Ni, 20 Cr, 15 W, rem Co
HS-31 (X-40)	0.50 C, 10 Ni, 25 Cr, 7.5 W, rem Co
HS-188	0.08 C, 22 Ni, 22 Cr, 14 W, 1.5 Fe, 0.08 La
S-816	0.40 C, 20 Ni, 20 Cr, 4 Mo, 4 Cb, 4 W, rem Co
UMCo 50	0.06 C, 28 Cr, 2.2 Mo, 20 Fe, 49 Co
WI 52	0.40 C, 21 Cr, 1 Ni, 2 Fe, 11 W, 2 Cb, rem Co

Waspaloy; Waspaloy filler metal (AMS 5828)



Joint type	Butt
Weld type	Square groove
Power supply	200 to 300-amp transformer-rectifier, with drooping voltage
Tack Welding	
Welding process	Manual gas tungsten-arc
Torch	Manual, water cooled
Electrode	1/16-in.-diam EWTh-2
Filler metal	None
Current	40 amp, dcsp
Voltage	9 to 11 v
Shielding gas:	
At torch	Argon, at 15 cfh
Backing gas	Argon, at 5 cfh
Welding position	Flat
Continuous Welding	
Welding process	Automatic gas tungsten-arc
Torch	Mechanical, water cooled
Electrode	1/16-in.-diam EWTh-2
Electrode extension	5/16 in. max
Arc starting	High frequency
Current	135 amp, dcsp
Voltage	11 v
Welding speed	16 ipm
Filler metal	0.032-in.-diam Waspaloy (AMS 5828)
Filler-metal feed	Automatic at constant speed
Filler-metal speed	30 ipm
Shielding gas:	
At torch	Argon, at 30 cfh; helium, at 2 cfh
Backing gas	Argon, at 5 cfh
Trailing shield	Argon, at 25 cfh
Welding position	Flat (electrode holder, fixed; workpiece, revolved)
Number of passes	One

Fig. 1. Waspaloy air-seal ring and method of holding components for gas tungsten-arc welding (Example 271)

Nickel-Base Heat-Resisting Alloys

Some nickel-base heat-resisting alloys (see Table 1) are solid-solution strengthened, and others are strengthened by the precipitation of a second phase from a supersaturated solid solution. Many of the solid-solution nickel-base alloys, including Inconel 600, Hastelloy B and Hastelloy C, are widely used in applications requiring resistance to corrosion at temperatures ranging from cryogenic to 800 F or higher; these alloys, therefore, are classified as being *both* heat-resisting and corrosion-resisting. Welding of other corrosion-resisting nickel-base alloys, including nickel-copper alloys, is discussed in the article on Arc Welding of Nickel Alloys, which begins on page 366 in this volume.

The nickel-base alloys are commonly welded by the gas tungsten-arc and shielded metal-arc processes. Gas metal-arc welding is used for joining sections more than ⅜ in. thick. Grooves in thick metal require a large amount of filler metal, and because of their bulk, such sections can withstand the heat input characteristic of the gas metal-arc process. Frequently, a root pass is made by gas tungsten-arc welding, and the filler passes by gas metal-arc welding. Submerged-arc welding is used, but the welding flux must be carefully selected to obtain adequate protection, and the welding conditions chosen must avoid excessive heat input. When welding metal more than 3 in. thick, shrinkage stresses will decrease ductility slightly, and a postweld stress-relieving treatment may be necessary.

Precipitation-hardenable alloys are susceptible to cracking in the weld metal or in the heat-affected zone unless they are properly heat treated before and after welding. The alloys containing columbium and tantalum, such as alloy 718, have a relatively slow hardening response and can be welded without undergoing spontaneous hardening during heating and cooling.

The nickel-chromium and nickel-molybdenum solid-solution alloys are readily welded in the annealed condition. No heat treatment is needed after welding to improve corrosion resistance, and generally the alloys do not become embrittled after long exposure at temperatures up to about 1500 F.

Table 2 lists general conditions for gas tungsten-arc welding of heat-resisting nickel-base alloys.

Table 2. Conditions for Gas Tungsten-Arc Welding of Heat-Resisting Alloys(a)

Base-metal thickness, in.	Diameter of filler metal, in.(b)	Electrode diameter, in.(c)	Shielding gas: Gas	Shielding gas: Flow rate, cfh	Welding current, amp(d)
0.010	0.020	0.040 to 0.060	Argon	12 to 15	10 to 15
0.020	0.030	0.060	Argon	12 to 15	15 to 25
0.030	0.030; 0.045	0.060	Argon	12 to 15	25 to 35
0.045	0.045	0.060	Argon	12 to 15	40 to 50
0.050	0.045	0.060	Argon	12 to 15	45 to 55
0.060	0.045	0.060	Argon	12 to 15	55 to 65
0.080	0.060	0.060	Argon	12 to 15	75 to 85
0.100	0.060; 0.090	0.093	A or He	12 to 20	95 to 105
0.125	0.060; 0.090	0.093	A or He	12 to 20	110 to 135
0.250	0.060; 0.090	0.093	A or He	12 to 20	130 to 200

(a) The data in this table are intended to serve as starting points for the establishment of optimum machine settings for welding workpieces on which previous experience is lacking. They are subject to adjustment as necessary to meet the special requirements of individual applications. These data are the result of experience in welding Hastelloy alloys B, C, C276, F, N and X; Inconel alloys 600, 625, 718, 722 and X-750; nickel-base alloy René 41; iron-base alloys A-286 and N-155; and cobalt-base alloys HS-25 (L-605) and HS-188. Torch-nozzle diameter was $\frac{7}{16}$ in.; nozzle had a gas lens. (b) Minimum wire diameters, where applicable. (c) EWTh-2 electrodes, tapered to a point. (d) Straight-polarity direct current with high-frequency arc starting. An increase of 10 to 20 amp may be needed for melt-through T-joints.

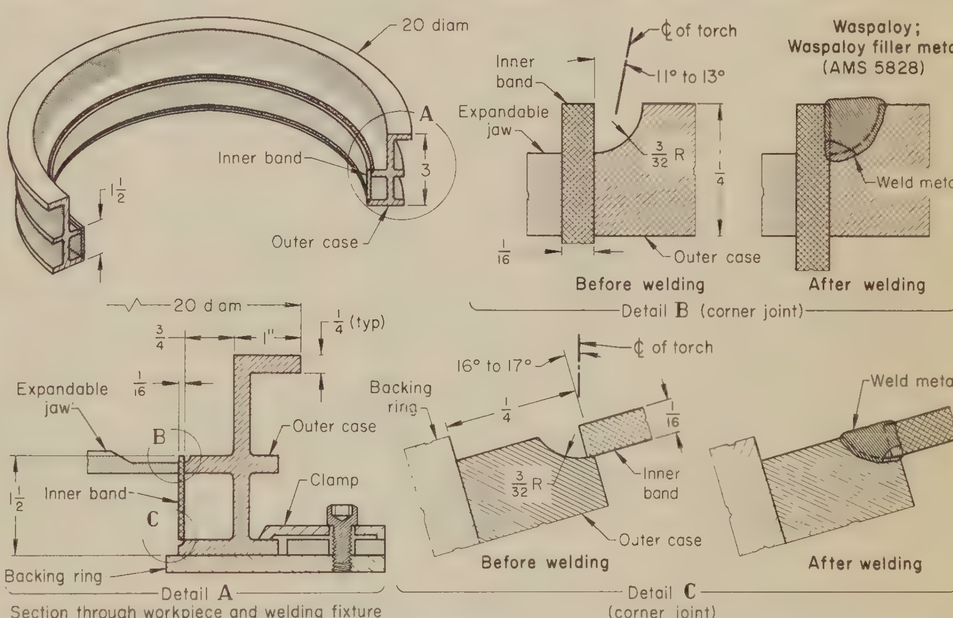
Joint Design for Nickel-Base Alloys

The same joint designs are used for both gas tungsten-arc and shielded metal-arc welding. Joint design for gas metal-arc welding requires special consideration, as discussed in the section on Gas Metal-Arc Welding of Nickel-Base Alloys, page 285. Unless it has been proven satisfactory by experience, a joint design that has been developed for another metal should not be used for nickel-base alloys.

Table 3 shows joint designs used in welding nickel-base heat-resisting alloys, and gives the sizes of grooves or welds in different metal thicknesses and the approximate amount of metal deposited. Nickel-base alloy weld metal does not flow as readily as steel weld metal does. Therefore, the molten metal will not penetrate as deeply as steel weld metal, and so the joints must be more open, to permit electrode or filler-metal manipulation and the placement of weld metal. Excessive puddling and heat input have a detrimental effect, inasmuch as loss of residual deoxidizers may result.

Preweld and Postweld Heat and Mechanical Treatments for Nickel-Base Alloys

The solid-solution (non-age-hardenable) alloys are welded in the annealed condition, sometimes after slight cold working. The precipitation-hardenable alloys usually are welded in the solution-treated condition, although test data indicate that welding René 41 in



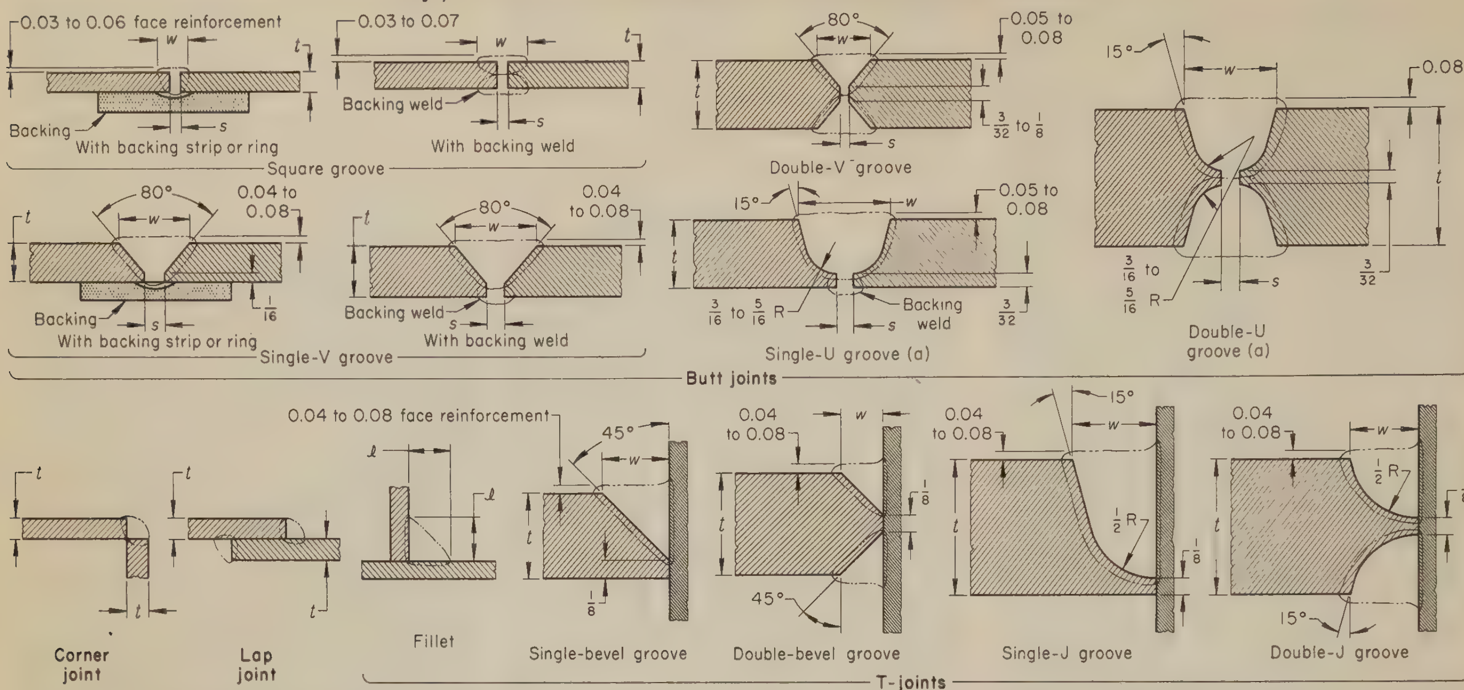
Welding Conditions	
Joint type	Corner
Weld type	Single-J groove
Welding process	Automatic gas tungsten-arc
Power supply	200 to 300-amp transformer-rectifier, with drooping voltage
Torch	Water cooled
Electrode	$\frac{3}{32}$-in.-diam EWTh-2, tapered to 0.025-in. diameter
Electrode extension	$\frac{5}{16}$ in. max
Arc starting	High frequency
Filler metal:	
First pass	None
Second pass	0.032-in.-diam Waspaloy
Filler-metal feed	Adjustable at constant speed
Filler-metal speed	16 ipm
Shielding gas:	
At torch	Argon, at 30 to 35 cfh
On fixture	Argon, at 40 cfh; purge 5 min before welding
Edge preparation	Machine grooves in outer case; wipe both parts with methyl ethyl ketone

Corner Joint Shown in Detail B	
Current:	
First pass	100 to 105 amp, dcsp
Second pass	140 to 150 amp, dcsp
Voltage:	
First pass	10 v
Second pass	11 to 12 v
Welding speed	8.5 to 9.5 ipm
Welding position:	
Positioner	Flat
Torch	Tilted 11° to 13° from vertical

Corner Joint Shown in Detail C	
Current:	
First pass	80 to 85 amp, dcsp
Second pass	100 to 105 amp, dcsp
Voltage	10 to 11 v
Welding speed	8.5 to 9.5 ipm
Welding position:	
Positioner	Tilted 73° to 74° from horizontal
Torch	Vertical

Fig. 2. Turbine-shroud ring assembly and fixture used for holding joints for automatic gas tungsten-arc welding. Positioning of joint and torch for welding are shown in details B and C. (Example 272)

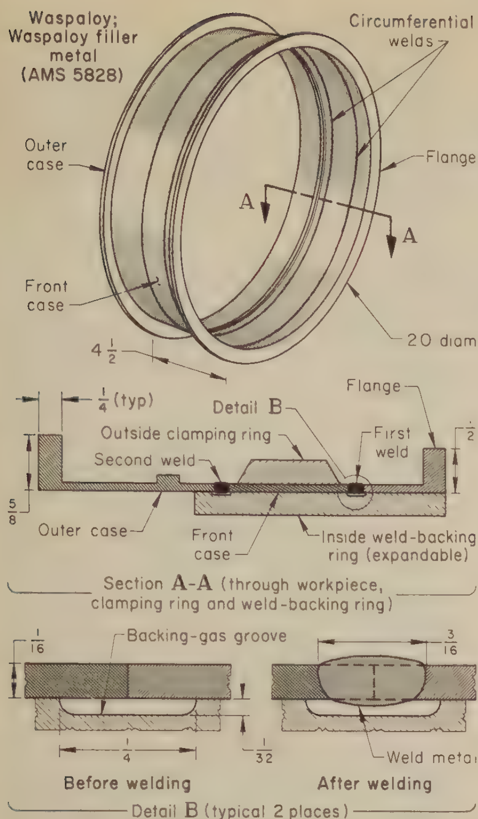
Table 3. Joint Designs and Dimensions for Gas Tungsten-Arc, Gas Metal-Arc, and Shielded Metal-Arc Welding of Nickel-Base Heat-Resisting Alloys, and Amount of Filler Metal and Consumable Electrode Required



Base-metal thickness (t), in.	Width of groove or bead (w), in.	Maximum root opening (s), in.	Approximate amount of metal deposited per linear foot, Cu in.	Lb	Approx weight of electrode required per linear ft, lb(a)
Square-Groove Butt Joint With Backing Strip or Ring					
0.037	1/8	0	0.07	0.02	0.025
0.050	5/32	0	0.13	0.04	0.05
0.062	3/16	0	0.13	0.04	0.06
0.093	3/16 to 1/4	0 to 1/32	0.18	0.06	0.08
0.125	1/4	1/32 to 1/16	0.22	0.07	0.09
Square-Groove Butt Joint With Backing Weld					
1/8	1/4	0 to 1/32	0.35	0.11	0.15
3/16	3/8	1/32 to 1/16	0.74	0.24	0.32
1/4	7/16	1/16 to 3/32	0.97	0.31	0.42
Single-V-Groove Butt Joint With Backing Strip or Ring					
3/16	0.35	1/8	0.72	0.227	0.31
1/4	0.51	3/16	1.39	0.443	0.61
5/16	0.61	3/16	1.84	0.582	0.80
3/8	0.71	3/16	2.36	0.745	1.02
1/2	0.91	3/16	3.68	1.16	1.59
5/8	1.16	3/16	5.10	1.61	2.21
Single-V-Groove Butt Joint With Backing Weld					
1/4	0.41	3/32	1.33	0.42	0.58
5/16	0.51	3/32	1.71	0.54	0.74
3/8	0.65	1/8	2.30	0.73	1.00
1/2	0.85	1/8	3.85	1.21	1.67
5/8	1.06	1/8	4.63	1.46	2.00
Double-V-Groove Butt Joint					
1/2	0.40	1/8	2.65	0.89	1.16
5/8	0.49	1/8	3.45	1.08	1.48
3/4	0.62	1/8	4.60	1.46	2.00
1	0.81	1/8	7.70	2.42	3.34
1 1/4	1.03	1/8	9.26	2.92	4.00
Single-U-Groove Butt Joint(b)					
1/2	0.679	1/8	3.27	1.03	1.41
5/8	0.745	1/8	4.37	1.38	1.90
3/4	0.813	1/8	5.33	1.68	2.30
1	0.957	1/8	8.35	2.63	3.60
1 1/4	1.073	1/8	11.48	3.62	4.96
1 1/2	1.215	1/8	15.16	4.79	6.55
1 3/4	1.349	1/8	18.90	5.98	8.19
2	1.485	1/8	23.45	7.40	10.12
Double-U-Groove Butt Joint(b)					
1	0.679	1/8	6.54	2.06	2.82
1 1/4	0.745	1/8	8.74	2.76	3.80
1 1/2	0.813	1/8	10.66	3.36	4.60
2	0.957	1/8	16.66	5.26	7.20
2 1/2	1.073	1/8	22.96	7.24	9.92

(a) To obtain linear feet of weld per pound of consumable electrode, take the reciprocal of pounds per linear foot. If the underside of the first bead is chipped out and welded, add 0.21 lb of metal deposited (equivalent to 0.29 lb of consumable electrode). (b) For gas metal-arc welding (except with the short-circuiting arc), root radius should be one-half the value shown and bevel angle should be twice as great.

Base-metal thickness (t), in.	Width of groove (w), in.	Size of fillet (l), in.	Approximate amount of metal deposited per linear foot, Cu in.	Lb	Approx weight of electrode required per linear ft, lb(a)
Corner and Lap Joint					
1/16	....	....	0.05	0.02	0.04
1/8	....	....	0.15	0.05	0.07
3/16	....	....	0.33	0.10	0.14
1/4	....	....	0.59	0.19	0.26
3/8	....	....	1.32	0.42	0.57
1/2	....	....	2.35	0.74	1.02
T-Joint With Fillet Weld					
....	....	1/8	0.09	0.03	0.04
....	....	3/16	0.22	0.07	0.10
....	....	1/4	0.38	0.12	0.16
....	....	5/16	0.59	0.19	0.26
....	....	3/8	0.84	0.27	0.37
....	....	1/2	1.50	0.47	0.64
....	....	5/8	2.34	0.74	1.01
....	....	3/4	3.38	1.07	1.46
....	....	1	6.00	1.90	2.60
Single-Bevel-Groove T-Joint					
1/4	0.125	....	0.22	0.07	0.09
5/16	0.188	....	0.40	0.13	0.17
3/8	0.250	....	0.61	0.19	0.26
1/2	0.375	....	1.21	0.38	0.52
5/8	0.500	....	1.98	0.63	0.86
3/4	0.625	....	2.95	0.93	1.28
1	0.875	....	5.57	1.77	2.42
Double-Bevel-Groove T-Joint					
1/2	0.188	....	0.78	0.25	0.34
5/8	0.250	....	1.24	0.39	0.54
3/4	0.313	....	1.78	0.56	0.77
1	0.438	....	3.13	0.99	1.36
1 1/4	0.563	....	4.87	1.54	2.15
1 1/2	0.688	....	7.00	2.21	3.03
1 3/4	0.813	....	9.47	3.00	4.09
2	0.938	....	12.33	3.90	5.35
Single-J-Groove T-Joint					
1	0.625	....	5.64	1.78	2.4
1 1/4	0.719	....	7.91	2.50	3.4
1 1/2	0.781	....	10.20	3.23	4.4
1 3/4	0.875	....	12.95	4.09	5.6
2	0.969	....	15.60	4.93	6.8
2 1/4	1.031	....	18.35	5.80	8.0
2 1/2	1.094	....	21.95	6.94	9.5
Double-J-Groove T-Joint					
1	0.500	....	4.67	1.48	2.0
1 1/4	0.563	....	6.90	1.90	2.6
1 1/2	0.594	....	8.10	2.56	3.5
1 3/4	0.625	....	9.83	3.11	4.3
2	0.656	....	12.06	3.81	5.2
2 1/4	0.688	....	14.29	4.51	6.2
2 1/2	0.750	....	16.68	5.27	7.2



Joint type	Butt
Weld type	Square groove
Welding process	Automatic gas tungsten-arc
Power supply	200 to 300-amp transformer-rectifier, with drooping voltage
Torch	Mechanical, water cooled
Electrode	3/32-in.-diam EWTh-2, tapered to 0.025-in. diameter
Electrode extension	1/4 in. max
Arc starting	High frequency
Current:	
First weld	65 to 70 amp, dcsp
Second weld	70 amp, dcsp
Voltage (both welds)	9 to 9 1/2 v
Welding speed:	
First weld	11 ipm
Second weld	13 1/2 ipm
Filler metal	0.032-in.-diam Waspaloy
Filler-metal feed	Constant speed, with feedback control
Filler-metal speed	20 ipm (approx)
Shielding gas:	
At torch	Argon, at 30 to 35 cfh
Backing gas	Argon, at 8 to 10 cfh
Welding position	Flat
Number of passes	One

Fig. 3. Waspaloy gas-turbine shroud that was made by gas tungsten-arc welding three ring-shape parts in two single-pass circumferential welds (Example 273)

the overaged condition can help prevent strain-age cracking. If a high degree of deformation should occur during preweld forming, or if the alloy has a high work-hardening rate, process annealing on the formed workpieces, before welding, may be required. Usually, preheating of nickel-base heat-resisting alloys is neither needed nor recommended. A postweld thermal or mechanical treatment usually is needed, especially for the precipitation-hardenable alloys, to redistribute and relieve residual stresses resulting from weld-shrinkage strains. Often, both treatments are used on the same weldment.

Mechanical stress-relieving treatments include tensile stretching, roll planishing, and peening. Control of these treatments is erratic, and complete relief of residual stresses by mechanical techniques is difficult to accomplish. Mechanical stress relieving is most effective in redistributing residual stresses in a single direction. Effective stress relieving by roll planishing requires that the weld shape be uniform.

Heat treatments produce more uniform reductions in residual-stress patterns than do mechanical treatments and are preferred for stress relief. They can be combined with hot sizing, where required, to produce parts to close dimensional tolerances.

Weldments made of solid-solution alloys can be used as-welded or after stress relieving, depending on the alloy and application. Stress relieving in the range from 800 to 1600 F, depending on the alloy and its condition, can be used to reduce or remove stresses in work-hardened solid-solution alloys without producing a recrystallized grain structure, and a low-temperature stress-equalizing heat treatment (600 to 800 F) can be used to redistribute stresses without appreciably decreasing the mechanical strength produced by the previous cold working.

Precipitation-hardenable alloys are given a solution treatment after welding to relieve residual stresses, and then they are hardened by an aging heat treatment. If the normal aging time or temperature is exceeded, overaging will occur; it can result in loss of strength and increase in ductility.

In the following example, excessive distortion of the weldment was encountered during postweld solution treating, and the heat treatment was modified so that acceptable parts could be produced.

Example 273. Modification of Postweld Heat Treatment To Minimize Distortion (Fig. 3)

The gas-turbine shroud shown in Fig. 3 required two circumferential welds to join an outer case, a front case, and a flange, all made of Waspaloy. Single-pass welds were made by automatic gas tungsten-arc welding.

Waspaloy is susceptible to strain-age cracking. This type of failure can occur in service in the temperature range of 1200 to 1500 F. Weldment components, therefore, usually are solution treated prior to welding and, after welding, are again solution treated at about 1975 F for 1 hr and then aged at 1400 F for 16 hr. In this instance, excessive distortion was encountered during solution treatment, and therefore a modified heat treatment was developed that consisted in solution treating the components between rough and finish machining (prior to welding) and aging the weldments at 1600 F for 1 hr and at 1400 F for 10 hr.

Joint areas were cleaned by wiping with methyl ethyl ketone, and parts were handled with white gloves. The assembly was held together in a fixture with an expandable inside weld-backing ring that forced the assembly against an outside ring, as shown in Fig. 3. The inside ring was relieved at the roots of the joints for backing-gas flow, and the assembly was purged with argon gas for 5 min before welding was started. Welding details are summarized in the table that accompanies Fig. 3.

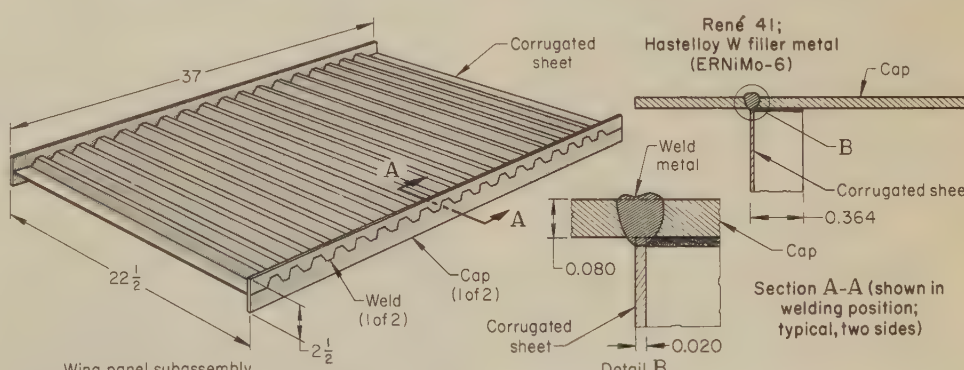
Welds were inspected for surface cracks before and after heat treatment by fluorescent-penetrant techniques, and for internal cracks by x-ray radiography.

Another unconventional heat treatment, which involved stress relieving René 41 weldments at 1000 F before age hardening, in order to prevent strain-age cracking, was successfully applied to test parts in an evaluation program. The results, which do not include service experience, are described in the example that follows.

Example 274. Stress Relieving a René 41 Weldment To Prevent Strain-Age Cracking (Fig. 4)

The wing-panel subassembly shown in Fig. 4 was made by joining a 0.020-in.-thick corrugated sheet, which had been cold worked by forming, and two 0.080-in.-thick side caps. The metal had been purchased in the solution-treated condition (AMS 5545, solution treated at 1975 ± 25 F) and was used as-received. The caps were manually gas tungsten-arc welded to the corrugated sheet, using the melt-through technique, a weld fillet being formed on both sides of the corrugated sheet. Filler metal was Hastelloy W (ERNiMo-6).

The weldment was stress relieved at 1000 F for 5 hr, furnace cooled to 500 to 600 F, air cooled to room temperature, age hardened at 1400 F for 16 hr, and air cooled. The 1000 F stress relief was advantageous because 25 to 35% of the contraction (normally, 0.001 in. per inch) expected during age hardening was achieved with little hardening. Thus, the assembly was able to deform plastically without cracking. This was especially significant because cold worked components and solution-treated components, with different rates of contraction, were joined. Also, the assembly



Joint type	T
Weld type	Melt-through fillet
Welding process	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier
Torch	Water cooled
Electrode	1/16-in.-diam EWTh-2
Filler wire	1/16-in.-diam Hastelloy W (ERNiMo-6)
Shielding gas	Argon, at 20 cfh
Current	150 to 250 amp, dcsp
Voltage	12 to 15 v
Welding position	Flat

Fig. 4. René 41 wing-panel subassembly that was manually gas tungsten-arc welded, followed by low-temperature stress relieving before age hardening (Example 274)

Table 4. Conditions for Gas Tungsten-Arc Welding of Hastelloy X, Inconel 600 and Waspaloy

Item	Hastelloy X — Manual welding	Hastelloy X — Automatic welding	Inconel 600, manual welding	Waspaloy, manual welding
Base-metal thickness, in.	0.062	0.062	¼ to ⅜	0.045 to 0.062
Joint type	Square butt(a)	Square butt(a)	V-groove butt(b)	Square butt(a)
Electrode	3/32-in.-diam EWTh-2(b)	3/32-in.-diam EWTh-2(c)	3/32-in.-diam EWTh-2(c)	3/32-in.-diam EWTh-2(c)
Filler metal	0.045 and 0.062-in.-diam Hastelloy X (AMS 5798)	0.035-in.-diam Hastelloy X (AMS 5798)	1/16 and 3/32-in.-diam Inconel 82 (ERNiCr-3)	0.045 and 0.062-in.-diam Waspaloy (AMS 5828)
Number of passes	One	One	Five to seven	One
Welding speed, ipm	4 to 5	10 to 15	2 to 3	2 to 3
Wire feed, ipm	...	18 to 32	...	...
Current (dcsp), amp	80 to 90	90 to 100	80 to 130	60 to 80
Voltage, v	10 to 12	8 to 10	10 to 14	9 to 11
Arc starting	High frequency	High frequency	High frequency	High frequency
Shielding gas:				
At torch	Argon, at 15 to 20 cfh	Argon, at 20 cfh	Argon, at 20 cfh	Argon, at 15 to 20 cfh
Backing gas	Argon, at 5 to 10 cfh	Argon, at 3 to 5 cfh	Argon, at 3 to 5 cfh	Argon, at 5 to 10 cfh
Preheat and postheat	None	None	None(d)	None

(a) Zero root opening for welds from ¼ to 2 in. long; 1/32 to 3/64-in. root opening for welds from 2 to 4 in. long. (b) 3/32 to ⅛-in. root face, 80° included angle. (c) Electrode tapered to 1/64-in. diameter. (d) Interpass temperature, 350 F max.

could be straightened after stress relieving and before age hardening, if necessary.

Although stress relieving René 41 at 1000 F before aging is unusual, because residual stresses are not substantially reduced at this temperature, the 1000 F heat treatment prevented strain-age cracks from occurring in the base metal. Also, the use of a solid-solution filler metal (Hastelloy W) instead of a precipitation-hardenable filler metal reduced strain-age cracking in the weld.

The welds were inspected visually and by the dye-penetrant method. A summary of the welding conditions is given in the table that accompanies Fig. 4.

Copper chill and hold-down bars, machined to the contour of the corrugations, were used for welding the cap to the sheet.

Overaging René 41. Recent tests conducted with circular-patch test specimens made of René 41 plate (0.60 in. thick) have indicated that this alloy is more resistant to strain-age cracking when preweld solution heat treated at 1975 F and overaged than when solution heat treated at 2150 F or when mill annealed at 1950 F and then aged at 1400 F for 16 hr. The preweld overaging treatment consisted of holding at progressively lower temperatures as follows:

1. Solution treat at 1975 F for ½ hr, cool at 3 to 8 F per minute to 1800 F
2. Hold at 1800 F for 4 hr, cool at 3 to 8 F per minute to 1600 F
3. Hold at 1600 F for 4 hr, cool at 3 to 8 F per minute to 1400 F
4. Hold at 1400 F for 16 hr, air cool to room temperature.

An alternative overaging treatment was simply to cool slowly (50 to 100 F per hour) from the 1975 F solution treating temperature. Although ductility was decreased slightly, the tensile and rupture strengths of René 41 were completely recovered by the conventional solution and aging heat treatment after welding.

Gas Tungsten-Arc Welding of Nickel-Base Alloys

Nickel-base heat-resisting alloys are readily weldable by the gas tungsten-arc process. Thin sections of aluminum-containing, precipitation-hardenable alloys are frequently joined without filler metal. The addition of filler metal is usually recommended for solid-solution alloys.

Straight-polarity direct current is recommended for both manual and machine gas tungsten-arc welding. The welding arc is started by a high-frequency current. An extension on the workpiece, which is machined off before the weldment is put into service, is frequently used to assure full-penetration welds and to minimize cracks in the weld metal caused by starts and stops. Heat input is kept as low as possible, to minimize the heat-affected zone. General conditions for gas tungsten-arc welding of nickel-base alloys are summarized in Table 2; specific conditions for welding three nickel-base alloys — Hastelloy X, Inconel 600 and Waspaloy — are given in Table 4.

For details of the gas tungsten-arc welding process, see the article that begins on page 113 in this volume.

Shielding Gas. Argon, helium, or a mixture of argon and helium is used as shielding gas. Helium produces a hotter arc, and frequently permits use of higher welding speeds. In Table 5, which suggests settings for welding nickel-base alloy 718 using argon and helium shielding, the recommended current is lower for helium, voltage is higher, and wire-feed rate is lower, for the same welding speed.

Welding grade argon and helium should be used; oxygen, carbon dioxide or nitrogen in the shielding gas usually will cause porosity and should not be present. An addition of about 5% hydrogen to argon acts as a reducing agent and is sometimes beneficial when the work metal has not been thoroughly cleaned. However, argon with 5% hydrogen should be used only for first-pass or single-pass welding, because porosity will result if this mixture is used for subsequent passes in multiple-pass welding.

In the following example, weld porosity due to inadequate cleaning was minimized by using an argon-helium-hydrogen shielding-gas mixture.

Example 275. Changing Composition of Shielding Gas To Control Porosity in Welds in Hastelloy C (Fig. 5)

Weld porosity due to inadequate cleaning was a problem in producing 3 to 12-in.-diam welded tubes from Hastelloy C sheet, 0.018 to 0.035 in. thick. A typical tube was 10 in. in diameter and 5 ft long. Tube seams were gas tungsten-arc welded in a seam welding machine that provided accurate joint alignment by clamping the joint edges between hold-down fingers and a backing bar, as shown schematically in Fig. 5(a). A Hastelloy C (ERNiMo-5) filler-metal wire was automatically fed. Originally, pure argon was used for shielding, both at the torch tip and in the backing groove. Torch travel was controlled by a motorized carriage operated by rack-and-pinion drive from a fixed overhead track.

Table 5. Conditions for Automatic Gas Tungsten-Arc Welding of 0.045-In.-Thick Nickel Alloy 718 Based on the Shielding Gas Used

Item	Shielding gas — Argon	Shielding gas — Helium
Current (dcsp), amp	80	40
Voltage, v	8 to 16	16 to 18
Welding speed, ipm	8	6 to 8
Filler-wire diam, in.	0.030-0.035	0.030-0.035
Wire-feed rate, ipm	12 to 15	8 to 9
Torch gas flow, cfh	20 to 24	20
Backing gas flow, cfh	4	4

Before welding, the joint edges were cleaned mechanically and chemically, but because the metal was resistant to chemical cleaning, joints still contained foreign material, which caused weld porosity. An investigation was carried out to determine if porosity could be avoided by using a different shielding gas. For the investigation, Hastelloy C test pieces were sheared from 0.026-in.-thick sheet and put through a slightly subnormal cleaning procedure to ensure that the test pieces would be susceptible to porosity. Then the test pieces were welded by the original procedure, except for the shielding gas used.

Shielding gas of high purity, premixed to various compositions, was purchased in tanks. On the assumption that a surface layer of oxide had been responsible for the porosity, a small amount of hydrogen, a reducing agent, was added to the shielding gas. In addition, helium was added to provide a hotter arc. An initial test using 98% argon, 2% hydrogen had given promising results and so a 5% hydrogen addition was tried with the argon and the various argon-helium mixtures. As helium content was increased from 0 to 45%, the porosity markedly decreased, until at 50% argon, 45% helium, 5% hydrogen, it was virtually eliminated (Fig. 5b). However, at this high helium concentration, the formability of the weld began to deteriorate (Fig. 5c).

The effect of welding speed was also investigated for the 50% argon, 45% helium, 5% hydrogen gas (Fig. 5d). Increasing welding speed from 10 to 30 in. per minute caused the porosity content of the weld to increase sharply. It appeared that by welding too rapidly, gas was trapped in the more rapidly solidifying welds.

The welds were examined by x-ray radiography and the number of pores was counted and recorded. Porosity (Fig. 5b and 5d) was expressed as the average number of pores per inch of weld metal in a minimum of 80 in. of weld.

Details of the welding conditions used in the investigation are summarized in the table that accompanies Fig. 5. As a result of the investigation, a shielding gas consisting of 60% argon, 35% helium and 5% hydrogen and a welding speed of 10 in. per minute were used for production welding.

Filler metals used with nickel-base heat-resisting alloys usually have the same general composition as the alloy

being welded. Because of the high arc currents and high welding temperatures, the compositions of the filler metals are often modified to resist porosity and hot cracking of the weld metal. Tack welding and root-pass welding frequently are done without filler metal. Table 6 gives the compositions of filler metals commonly used in gas tungsten-arc welding; several of these filler metals are used for welding metals other than nickel-base alloys.

For welding the precipitation-hardenable nickel-base alloys, either a precipitation-hardenable filler metal or a solid-solution filler metal may be used, depending on service requirements. Maximum mechanical properties, particularly in thick metal, are obtained when precipitation-hardenable filler metals are used, because most of the weld deposit is composed of filler metal. The solid-solution filler metals produce welds with lower mechanical properties, but they can be used where maximum strength is not needed. For example, when welding alloy 718 using filler metal René 41, alloy 718, GMR-235, or Hastelloy W (ERNiMo-6), weld specimens using the first three filler metals (precipitation-hardenable) gave tensile properties similar to those of the base metal, but Hastelloy W filler metal (solid-solution) gave weld tensile properties about 30% lower than those of the base metal.

Filler metal of the ERNiCr-3 classification (Table 6) is used for welding nickel-chromium-iron alloys to each other and to dissimilar metals, for high-temperature service and for nuclear applications.

Filler metal of the ERNiCrFe-5 classification is used to weld the nickel-chromium-iron alloys and Inconel 600. The columbium-plus-tantalum content minimizes hot cracking in the weld when high stress is developed, as when welding thick metal.

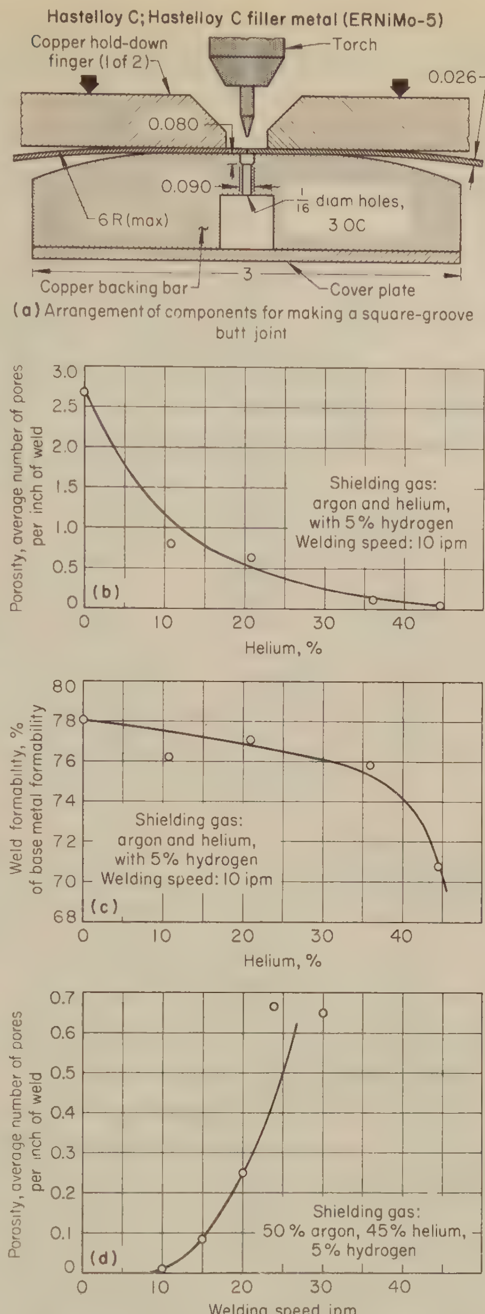
Filler metal of the ERNiCrFe-6 classification is used for welding some combinations of dissimilar metals. The deposited weld metal will respond to age-hardening treatments. When age-hardening response is not needed, ERNiCr-3 filler metal should be used.

Filler metal ERNiCrFe-7 contains aluminum, titanium, columbium and tantalum, and is used for welding the precipitation-hardenable alloys. The deposited filler metal will respond to aging treatments. The weldment must be stress relieved prior to aging.

Filler metals of the ERNiMo-4 and ERNiMo-5 classifications are intended for welding the nickel-chromium-molybdenum alloys.

Filler metal of the ERNiMo-6 classification has essentially the same composition as filler metal of the ERNiMo-4 classification, with 5% additional chromium. It is used for welding dissimilar metals, iron-nickel-chromium alloys, cobalt-base alloys, and nickel-base alloys. It is not precipitation hardenable, but it can be used to weld precipitation-hardenable alloys when high strength is not needed.

The filler metals listed in Table 6 by trade name have no applicable AWS classifications, but most have AMS designations, which are given in the table. These filler metals are primarily used for welding alloys of the same composition, although they are sometimes used for welding alloys of a different composition. For instance, René 41 and GMR-235 filler metals have been used to weld alloy 718.



Joint type	Butt
Weld type	Square groove
Welding process	Automatic gas tungsten-arc
Electrode	3/32-in.-diam EWTh-2
Electrode extension	3/8 in. max
Filler metal	0.010-in.-diam Hastelloy C
Shielding gas	See charts
Current	55 to 60 amp, dcsp
Voltage	9 to 11 v
Power supply	Constant-current rectifier, with drooping voltage
Welding speed	See charts
Special equipment	Seam welder with copper hold-down and backing tooling

(a) Section of tubing positioned between hold-down fingers and backing bar. (b) Effect of helium content of shielding gas on porosity of weld metal. (c) Effect of helium content of shielding gas on formability of weld metal (Erichsen cup values averaged from five tests). (d) Effect of welding speed on porosity, using a mixture consisting of 50% argon, 45% helium, and 5% hydrogen as the shielding gas.

Fig. 5. Automatic welding of Hastelloy C tubing, and test results that prompted a change in shielding gas from pure argon to 60% argon, 35% helium, 5% hydrogen, using a welding speed of 10 in. per minute (Example 275)

Joint Design. All of the joints shown in Table 3 are weldable by the gas tungsten-arc process. When no filler metal is used, the sections to be joined must be held tightly together (zero root opening) to promote proper fusion. Table 3 gives the recommended groove dimensions for joints of each type and the amount of filler metal needed. Because nickel-base alloys have lower thermal conductivity than steel, when V, U or J-groove design is used, a slightly larger bevel angle than would be needed for steel is employed to ensure complete penetration. When welding nickel-chromium-iron alloys, V-grooves should be beveled to a 75° to 80° groove angle; U-grooves are beveled to a 30° groove angle, with a 3/16 to 5/16-in. radius. A J-groove should have a 15° bevel angle with a radius of at least 3/8 in.; a 1/2-in. radius is preferred. T-joints between members of different thickness should have bevel or J-grooves. When welding the nickel-chromium-molybdenum alloys, V-grooves are beveled to a groove angle of 60°; root opening is 1/16 to 3/32 in. for 1/4-in.-thick metal and 3/32 to 1/8 in. for 1/2-in.-thick metal.

A square-groove butt joint in metal up to 1/8 in. thick can be made by welding on one side only, by using the proper root opening to provide full penetration. A backing strip usually is needed to produce good back reinforcement. Although a square-groove butt joint can be made in metal up to 1/4 in. thick provided that a backing weld is used, metal thicker than 0.125 in. should preferably be beveled and welded from both sides. When this is not practical, the root opening should be increased and a backing strip should be used to ensure full penetration. When butt welding two pieces of different thickness, the heavier section should be machined to the thickness of the thinner section at the joint for ease of welding and for better stress distribution.

Nonuniform penetration can result in undesirable crevices and voids in the underside of the joint, and can create stress raisers that act as focal points for mechanical failure in service.

When pipe or tubing is used to carry corrosive materials, backing rings should be avoided if they cannot be removed after welding. Crevices between the backing ring and the tube are highly susceptible to stress corrosion, which may cause root cracking.

When a product made of a precipitation-hardenable nickel-base alloy cannot be heat treated after welding (because of size or shape), the following technique can be employed. Connecting pieces made of a solid-solution alloy, or one that is unaffected by the welding heat, are welded on the joint side of each component of the product, and the components plus connecting pieces are given an aging heat treatment. Welding of the final product is done at the connecting pieces. The composition and location of the connecting pieces must

Table 6. Typical Compositions of Filler Metals and Electrode Wires for Arc Welding of Heat-Resisting Alloys

AWS classification or trade name	C	Mn	Fe	S	Si	Cu	Ni + Co(a)	Co	Al	Ti	Cr	Cb + Ta	Mo	Other, total
Nickel-Base Bare Electrodes for Gas Tungsten-Arc and Gas Metal-Arc Welding														
ERNiCr-3	0.10	2.5-3.5	3.0	0.015	0.50	0.50	67 min	(b)	...	0.75	18.0-22.0	2.0-3.0(c)	...	0.50
ERNiCrFe-5	0.08	1.0	6.0-10.0	0.015	0.35	0.50	70 min	...	...	...	14.0-17.0	1.5-3.0	...	1.0
ERNiCrFe-6	0.08	2.0-2.7	10.0	0.015	0.35	0.50	67 min	...	...	2.5-3.5	14.0-17.0	...	...	0.50
ERNiCrFe-7	0.08	1.0	5.0-9.0	0.01	0.50	0.50	70 min	...	0.40-1.00	2.00-2.75	14.0-17.0	0.70-1.20	...	0.50
ERNiMo-4	0.08	1.0	4.0-7.0	0.03	1.0	...	Rem	2.5	...	...	1.0	...	26.0-30.0	(d)
ERNiMo-5	0.08	1.0	4.0-7.0	0.03	1.0	...	Rem	2.5	...	...	14.5-16.5	...	15.0-17.0	(e)
ERNiMo-6	0.12	1.0	4.0-7.0	0.03	1.0	...	Rem	2.5	...	...	4.0-6.0	...	23.0-26.0	(f)
GMR-235	0.16	0.25	9.0-11.0	0.03	0.6	...	Rem	2.5	1.75-2.25	2.25-2.75	14.0-17.0	...	4.5-6.5	0.009 B
Hastelloy X (AMS 5798)	0.05-0.15	1.0	17.0-20.0	0.03	1.0	...	Rem	0.5-2.5	...	...	20.5-23.0	...	8.0-10.0	0.2-1.0 W
Inconel 601	0.05	0.5	14.1	0.007	0.25	0.25	60.5	...	1.35	...	23.0	...	...	...
Inconel 625 (AMS 5837)	0.10	0.5	5.0	0.015	0.5	...	Rem	1.0	0.4	0.4	20.0-23.0	3.15-4.15	8.0-10.0	...
Alloy 718 (AMS 5832)	0.08	0.35	Rem	0.015	0.35	0.3	50-55	1.0	0.2-0.8	0.65-1.15	17.0-21.0	4.75-5.5	2.8-5.5	(g)
René 41 (AMS 5800)	0.12	0.1	5.0	0.015	0.5	...	Rem	10.0-12.0	1.4-1.6	3.0-3.3	18.0-20.0	...	9.0-10.5	(h)
Waspaloy (AMS 5828)	0.07	0.10	0.75	...	0.1	...	Rem	13.5	1.4	3.0	19.75	...	4.45	(j)
Nickel-Base Covered Electrodes for Shielded Metal-Arc Welding														
ENiCr-1	0.15	1.5	4.0	0.015	0.75	0.50	70 min(a)	...	...	...	17.5 min	1.5-4.0	...	0.50
ENiCrFe-1	0.08	1.5	11.0	0.015	0.75	0.50	68 min(a)	...	...	...	13.0-17.0	1.5-4.0	...	0.50
ENiCrFe-2	0.10	1.0-3.5	6.0-12.0	0.020	0.75	0.50	Rem	...	...	...	13.0-17.0	0.5-3.0	0.5-2.5	0.50
ENiCrFe-3	0.10	5.0-9.5	6.0-10.0	0.015	1.0	0.50	Rem	(k)	...	1.0	13.0-17.0	1.0-2.5(m)	...	0.50
ENiMo-1	0.12	1.0	4.0-7.0	0.030	1.0	...	Rem	2.5	...	...	1.0	...	26.0-30.0	(n)
ENiMo-3	0.12	1.0	4.0-7.0	0.030	1.0	...	Rem	2.5	...	...	2.5-5.5	...	23.0-27.0	(n)
ENiMoCr-1	0.12	1.0	4.0-7.0	0.030	1.0	...	Rem	2.5	...	...	14.5-16.5	...	15.0-18.0	(p)
Inconel 112	0.10	0.5	5.0	0.015	0.50	...	Rem	1.0(a)	0.40	0.40	20.0-23.0	3.15-4.15	8.0-10.0	...
Iron-Nickel-Chromium, Iron-Chromium-Nickel and Cobalt-Base Heat-Resisting Alloy Filler Metals														
19-9 W (AMS 5782)	0.07-0.13	1.00-2.00	Rem	0.030	1.00	0.50	8.00-9.50	...	...	0.10-0.30	19.0-22.0	1.00-1.30	0.35-0.65	(q)
N-155 (AMS 5794)	0.1	1.00-2.00	Rem	0.030	1.00	...	19.00-21.00	18.5-21.0	...	...	20.0-22.5	0.75-1.25	2.5-3.5	(r)
A-286 (AMS 5804)	0.04-0.05	1.25-1.35	Rem	0.008	0.70	...	25	...	0.24-0.32	2.2	15	0.10-0.12	1.25	(s)
HS-25 or L-605 (AMS 5796)	0.10	1.5	3 max	...	10 max	...	10	Rem	...	...	20	...	...	15 W

(a) Cobalt, if determined, 1.0% max. (b) Cobalt, 0.10% max, when specified. (c) Tantalum, 0.30% max, when specified. (d) Vanadium, 0.20 to 0.60%; total of other elements, 0.50%. (e) Vanadium, 0.35%; tungsten, 3.0 to 4.5%; total of other elements, 0.50%. (f) Vanadium, 0.60%; total of other elements, 0.50%. (g) Phosphorus, 0.015%; boron, 0.006%. (h) Boron, 0.01%; total of other elements, 0.003%. (j) Boron, 0.005%; zinc, 0.04%.
(k) Cobalt, 0.12% max, when specified. (m) Tantalum, 0.30% max, when specified. (n) Vanadium, 0.60%; phosphorus, 0.04%; total of other elements, 0.50%. (p) Vanadium, 0.35%; tungsten, 3.0 to 4.5%; phosphorus, 0.04%; total of other elements, 0.50%. (q) Phosphorus, 0.04% max; tungsten, 1.25 to 1.75%. (r) Phosphorus, 0.040% max; tungsten, 2.00 to 3.00%. (s) Phosphorus, 0.02% max; boron, 0.0015 to 0.0022%.

be carefully selected so that welds are made in noncritical locations and so that service performance of the weldment is not adversely affected.

Corner and lap joints should be avoided if service temperatures are high or if service conditions involve thermal or mechanical cycling. When corner joints are used, a full-thickness weld must be made, such as that shown in Table 3. Usually, a fillet weld on the root side will also be required.

Joint design often affects selection of welding process and procedure. For example, when joining thin-wall tubes to tube sheets and tubes to flanged connections, and when welding bellows joints of various types, differential melting, caused by the varying heat-transfer capability of different base-metal thicknesses, may require special welding techniques. Sometimes, differential melting can be prevented by machining the thicker member to the same thickness as that of the thinner member or by suitable preheating of the thicker member. Directing the heat of welding to the thicker member is also beneficial. When these methods cannot be applied, a combination welding procedure may be successful, as in the example that follows.

Example 276. Use of Resistance Seam Welding Together With Gas Tungsten-Arc Welding To Produce a Leaktight Bellows Joint (Fig. 6)

A 10-in.-ID bellows assembly for a fuel duct for a rocket motor, shown in Fig. 6, consisted of a straight section of a 0.020-in.-thick bellows wall sandwiched between two 0.040-in.-thick rings, all made from alloy 718. A high-reliability seal weld was required. Originally, the joint was gas tungsten-arc welded, as follows: The acid-cleaned assembly was mounted on a rotating turntable and welded with 0.035-in.-diam alloy 718 (AMS 5832) filler metal under argon shielding gas. When the joint was tested hydrostatically under an internal pressure of 160 psi, the joint did not leak, but when it was tested with a helium mass spectrometer under an internal vacuum, significant leakage was detected.

After considerable investigation, it was determined that during welding the bellows wall melted back faster than the rings, so that weld metal was deposited at the edges of the rings only, resulting in a void that provided a leak path between the rings and the unintegrated surfaces of the bellows (see "After welding" view in detail A, Original method, in Fig. 6). One small void was enough to cause a leak.

The problem was solved by resistance seam welding and gas tungsten-arc welding the joint. The joint was first resistance seam welded (see Operation 1, Improved method, in Fig. 6) and then machined back to the edge of the seam weld. A gas tungsten-arc edge-flange weld was deposited as before (see Operation 2, Improved method, in Fig. 6). The completed combination weld was gastight under both methods of testing.

Conditions for gas tungsten-arc welding are summarized in the table with Fig. 6. Conditions for resistance seam welding are given in Example 386, in the article on Resistance Seam Welding.

Welding Techniques. When filler metal is used, the hot end of the wire must be kept under the shielding gas, and wire diameter should be no larger than work-metal thickness. The molten weld puddle must be kept as quiet as possible; otherwise, the deoxidizing elements will burn out.

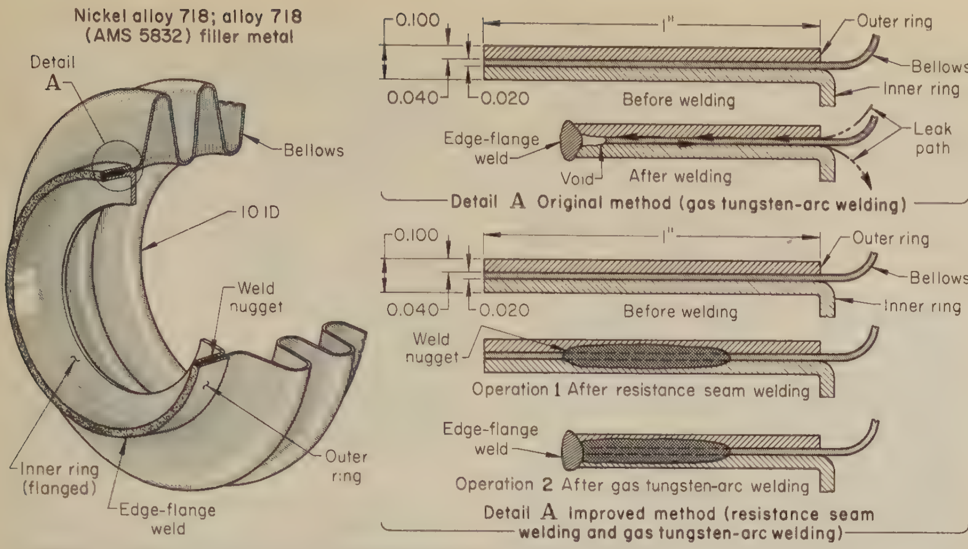
To ensure a sound weld, the arc must be maintained at the shortest possible length. When no filler metal is added, arc length should not exceed 0.05 in., and preferably should be 0.02 to 0.03 in. When filler metal is added, the arc will be longer, but it should be as short as possible, consistent with filler-metal diameter.

A greater-than-normal electrode extension will be needed for fillet welds and for the first few passes on heavy sections. Small-diameter filler-metal wires and more stringer passes may be used on welds made in other than the flat position, for adequate control of weld metal. When the back sides of butt welds do not show adequate penetration, they should be ground back to sound metal and back beads should be deposited. When possible, backing gas should be provided when welding the first side.

The following example describes procedures used to produce high-quality welds in a nuclear pressure vessel.

Example 277. Procedure for Making a Full-Penetration Circumferential Weld in Hastelloy X Pipe (Fig. 7)

A 6-in. elbow was manual gas tungsten-arc welded to the swaged end of a pressure vessel as shown in Fig. 7. The assembly, which was made entirely of Hastelloy X, was part



Conditions for Gas Tungsten-Arc Welding(a)

Joint type	Edge
Weld type	Three-member edge flange
Fixture	Rotating positioner
Power supply	300-amp transformer-rectifier
Electrode	0.040-in.-diam EWTh-2
Torch	300 amp, water cooled
Filler metal	0.035-in.-diam Inconel 718
Shielding gas	Argon, at 15 to 18 cfh
Current	50 to 55 amp, dcsp
Voltage	10 to 12 v
Arc starting	High frequency
Arc length	0.040 in. (approx)
Welding speed	60 ipm
Preweld cleaning	Immerse for 15 min in a solution of 30 to 40% HNO_3 and 2 to 5% HF

(a) For details of resistance seam welding, see Example 386, in this volume.

Fig. 6. Bellows joint of a rocket-motor fuel duct, and details showing how leaks occurred after gas tungsten-arc welding and how resistance seam welding together with gas tungsten-arc welding resulted in a leaktight joint (Example 276)

of a helium filter for the gas-cooled loop of a nuclear reactor. Fabrication was done in accordance with the ASME code for nuclear vessels and contract specifications.

The essential procedural conditions for welding are shown in Fig. 7 and described in the table that accompanies Fig. 7. Carefully selected practices were incorporated in the welding procedure to ensure high joint reliability, namely, for preweld cleaning, shielding, weld deposition, heat input control, and quality control.

Preweld Cleaning. Parts were received free of scale and with a bright finish. After the weld grooves had been machined (Fig. 7), the parts were immersed and scrubbed in unused, agitated acetone, and then wiped dry with a clean lint-free white cloth. No wire brushing or sanding was needed.

Shielding. In addition to torch shielding, a low positive-pressure argon flow was required for internal backing, to avoid oxidation at the weld root face and to limit root-face concavity to 3/32 in., as shown in Fig. 7. Before welding, the assembly was evacuated to 230 mm mercury, and then argon gas was introduced to bring the system up to atmospheric pressure. This was repeated five times to guarantee high purity of the argon during welding. Argon flows of 5 cu ft per hour at the root of the weld and 15 cu ft per hour at the torch were maintained during welding.

Positive internal pressure was assured by placing a plate with a ⅛-in.-diam hole over the open end of the elbow, and sealing the joint with tape. As welding advanced, the tape was removed about 3 in. ahead of the weld. Argon of certified welding quality (99.99% purity) was used. Any length of weld made during a cessation of gas flow was removed and rewelded. As an indication of adequate shielding, beads had to appear bright to dull gray after cooling.

Heat Control. To avoid any change in alloy phase distribution, and thus a change in alloy properties, heat input, interpass temperature, and postweld cooling were controlled. Heat input was controlled by depositing thin beads at low amperage. About 100 welding passes were needed to fill the joint. Interpass temperature was not allowed to exceed 150 F, and was measured by temperature-indicating crayons used on the base metal about ⅜ in. from the weld edge. Postweld cooling was assisted by water-cooling coils in which flow of the cooling water was regulated by a thermocouple placed inside the elbow near the weld and connected to a readout meter. When the joint became too warm, the water-cooling coils were activated.

Welding Technique. Arc-length control was important because of the sluggishness of the weld metal. A short arc had to be held at the weld puddle when filler metal was being deposited. High-frequency current was used for arc starting. Arc stops were made by leading the arc out of the groove to base metal, to avoid weld cracking. Slope control was used for regulating the current at the beginning and end of each weld pass. Tungsten electrodes were taper ground to a point and were maintained in a clean condition at all times.

Quality was ensured by: (*a*) procedure and welder qualification tests and other rules imposed by the ASME code for nuclear vessels; (*b*) dye-penetrant testing after the root pass and subsequent passes throughout the welding operation; (*c*) 100% radiographic inspection after the root pass and the final weld pass; (*d*) leak testing of the completed weld, using a helium leak-rate detector. The five joints welded by this procedure were acceptable.

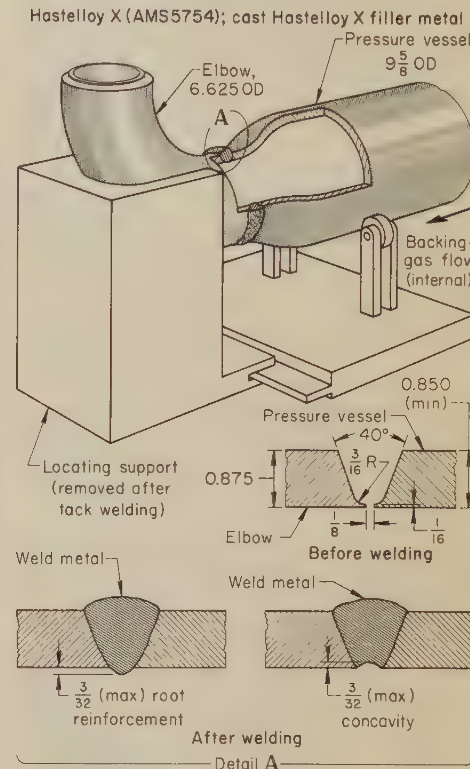
Gas Metal-Arc Welding of Nickel-Base Alloys

The solid-solution-strengthened nickel-base alloys and, with suitable welding procedures, many of the precipitation-hardenable alloys can be joined by gas metal-arc welding. Gas metal-arc welding is best suited to the joining of thick sections (more than about ⅜ in. thick) where high filler-metal deposition rates are desirable. For a description of this process, see the article on Gas Metal-Arc Welding, which begins on page 78.

Spray, globular, and short-circuiting metal transfer can be used. Optimum metal transfer is obtained when operating above the transition from globular to spray transfer. All of these methods employ electrode wire of comparatively small diameter. Incomplete fusion and oxide inclusions are likely to occur when the short-circuiting arc is used. Multiple-pass welds should be made by highly skilled welders only.

Reverse-polarity direct current should be used because the greater heating effect of reverse polarity assists in obtaining the required high melting rate.

Shielding gas for nickel-base heat-resisting alloys is argon or an argon-helium mixture. Gas flow rates range from 25 to 100 cu ft per hour, depending on joint design, type of metal transfer, and welding position. Gener-



Joint type	Butt
Weld type	Single-V groove
Welding process	Manual gas tungsten-arc
Power supply	500-amp constant-voltage transformer-rectifier, with slope control and gas preflow
Electrode	⅛-in.-diam EWTh-2 ground to a point
Torch	300 amp, water cooled; 7/16-in.-diam cup
Electrode extension	3/16 in. (approx)
Filler metal:	
Root pass	1/16-in.-diam cast Hastelloy X
Filler passes	3/32-in.-diam cast Hastelloy X
Shielding gas:	
At torch	Argon(a), at 15 cfh
Backing gas	Argon, at 5 cfh
Welding position	Horizontal-rolled pipe
Fixtures	Fit-up jig; turning rolls
Current	125 to 190 amp, dcsp (all passes)
Voltage	30 v
Interpass temperature	150 F max
Arc length	1/32 in. (approx)
Arc starting	High frequency(b)
Number of passes	100 (approx)
Travel speed	1 ipm
Preheat and postheat	None

(a) Welding grade, 99.997% pure. (b) Welding was terminated by leading the arc out of the groove to base metal. Slope control was used at beginning and end of each pass.

Fig. 7. Welding an elbow to a pressure vessel for a nuclear-reactor application, showing positioning of vessel for welding, joint design, and maximum root reinforcement and concavity (Example 277)

ally, flow rate is about 50 cu ft per hour. As the percentage of helium is increased, gas flow rate must be increased to give adequate protection.

Joint designs recommended for gas metal-arc welding are shown in Table 3. For the U-groove designs using globular or spray metal transfer, the root radius should be decreased by about 50% and the bevel angle should be doubled, compared with those shown in Table 3. When using a short-circuiting arc, the U-groove designs shown in Table 3 can be used without change.

Welding Techniques. Best results are obtained when the electrode holder is positioned at about 90° to the joint. Some inclination (up to about 15°) is permissible to permit a better view of the work, but excessive inclination can draw the surrounding atmosphere into the shielding gas, and porous or heavily oxidized welds will result.

Arc length is important. Weld spatter will occur if the arc is too short, and loss of control if the arc is too long.

The manipulation and electrode-holder angle used with pulsed-arc welding are similar to those used with shielded metal-arc welding. A slight pause at the limit of the weave is required in order to avoid an undercut.

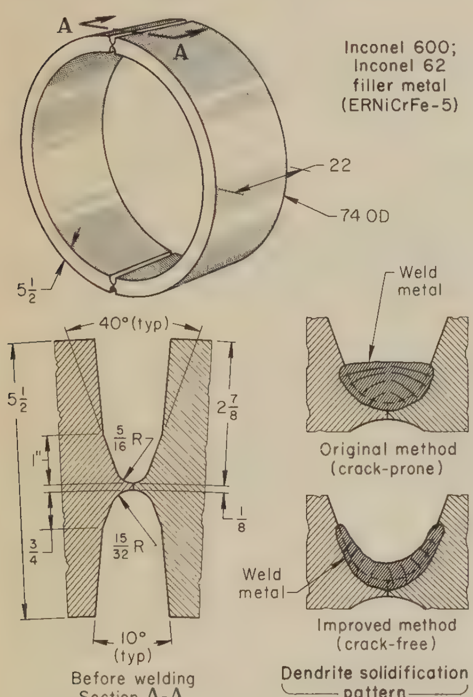
Electrode wire compositions for gas metal-arc welding are the same as those recommended for filler metals for gas tungsten-arc welding (Table 6). With globular and spray transfer, 0.035, 0.045 or 0.062-in.-diam wire is used. The short-circuiting arc generally requires wire 0.045 in. or less in diameter.

Production Examples. In the following example, thin weld beads covering the entire width of the groove were used to produce a crack-free weld. Because of the metal thickness, the design of the double-U groove was modified from that shown in Table 3.

Example 278. Prevention of Cracking in a Thick-Wall Cylinder by Using a Weaving Bead-Deposition Technique (Fig. 8)

Base-metal and weld-metal cracking were encountered in gas metal-arc welding of large 5½-in.-wall cylinders made of Inconel 600, because of hot shortness of the alloy and the solidification pattern produced by the welding technique (Original method, Fig. 8). By changing to a weave-bead technique, which produced a relatively wide, thin deposit, the direction of dendrite solidification was improved and heat concentration was decreased, resulting in crack-free base metal and welds. In deep, wide grooves, such as those shown in Fig. 8, section A-A, the amount of electrode holder oscillation and the travel speed were varied from layer to layer through the thickness of the groove, in order to produce optimum results.

Some welding conditions are given in the table that accompanies Fig. 8. With the aid of a skilled operator, the welds were produced by semiautomatic gas metal-arc welding.



Welding Conditions for Improved Method

Joint type	Butt
Weld type	Double-U groove
Welding process	Semiautomatic gas metal arc
Power supply	400-amp transformer-rectifier, with drooping voltage
Electrode	0.062-in.-diam Inconel 62
Shielding gas	Argon
Deposition rate	11 lb/hr, at 100% arc time

The wide, thin weld deposit produced by the weave-bead technique used in the improved method resulted in a lower heat gradient and a crack-free dendrite solidification pattern.

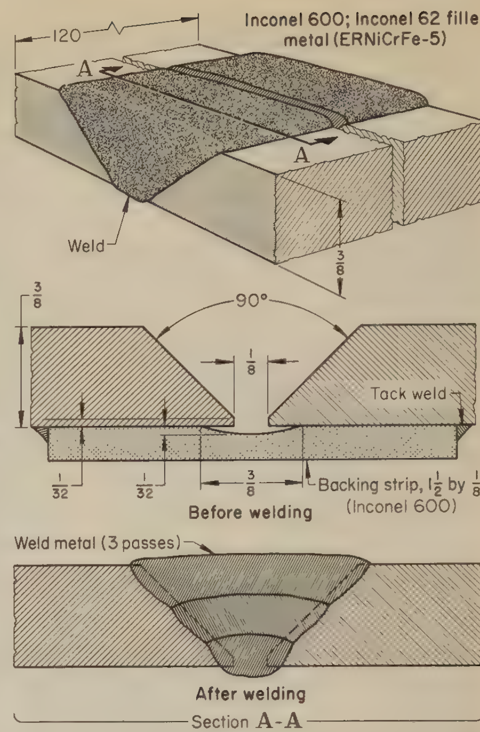
Fig. 8. Thick-wall cylinder that was welded by gas metal-arc welding. Joint design and original and improved solidification patterns. (Example 278)

In the next example, gas tungsten-arc welding was used for tack welding and gas metal-arc welding for root and filler passes in joining ⅜-in.-thick plate. The V-groove had an angle larger than the 80° angle suggested in Table 3.

Example 279. Use of Manual Gas Metal-Arc Welding for Joining ⅜-In.-Thick Plates of Inconel 600 (Fig. 9)

Because only a few welds were to be made and the available automatic equipment could not deposit a weaving bead, manual gas metal-arc welding was used to join 10-ft-long, ⅜-in.-thick plates of Inconel 600. A backing strip of Inconel 600 was temporarily tack welded, by manual gas tungsten-arc welding, to the back of the groove. Tack welds 1 in. long on 6-in. centers helped maintain the ⅛-in. root opening. The conditions for tack welding the backing strip and filling the groove are given in the table with Fig. 9.

A weaving technique was used for gas metal-arc welding to obtain a cellular type of weld solidification pattern (rather than dendritic), and thus to minimize the amount of segregation and provide good corrosion resistance.



Joint type	Butt
Weld type	Single-V groove
Welding process:	
Tack weld	Manual gas tungsten-arc
Groove weld	Manual gas metal-arc

Welding Conditions for Manual Gas Tungsten-Arc Tack Welding

Power supply	Transformer-rectifier, with drooping voltage
Electrode	3/32-in.-diam EWTh-2
Filler metal	0.045-in.-diam Inconel 62
Shielding gas	Argon, at 35 cfh
Welding position	Flat
Current	275 amp, dcsp
Voltage	27 to 29 v
Tack-weld spacing	1 in., on 6-in. centers

Welding Conditions for Manual Gas Metal-Arc Welding

Power supply	Constant-voltage transformer-rectifier
Electrode holder	Manual, water cooled
Electrode wire	0.045-in.-diam Inconel 62
Shielding gas	Argon, at 35 cfh
Current	275 amp, dcrp
Voltage	27 to 29 v
Welding position	Flat
Number of passes	Three
Setup and welding time per plate	1 hr, 50 min

Fig. 9. Plate of ⅜-in.-thick Inconel 600 that was welded by manual gas metal-arc welding, with joint design, backing strip and completed weld. The backing strip, tack welded in place by manual gas tungsten-arc welding, served as a fixture to maintain the root opening. (Example 279)

Shielded Metal-Arc Welding of Nickel-Base Alloys

Shielded metal-arc welding is widely used for joining the solid-solution nickel-base alloys, but is rarely used for joining the precipitation-hardenable alloys. The process is described in the article on Shielded Metal-Arc Welding, pages 1 to 23, this volume.

Reverse-polarity direct current is generally used to obtain optimum mechanical properties.

Joint design (see Table 3) must be such as to permit rapid travel and a minimum of weaving, in order to minimize heat input. Weaving is sometimes desirable, but the amount should not exceed three times the electrode diameter. Overheating can cause hot-short cracking in the weld metal or the base metal, and excessive carbide precipitation at grain boundaries in the heat-affected zone.

Electrodes for shielded metal-arc welding are listed in Table 6. Electrode composition should be similar to that of the base metal with which the electrode is to be used.

Electrodes of the ENiCr-1 classification are used for welding nickel-base alloys where high chromium content of weld metal must be maintained in spite of dilution by iron — for example, in welding nickel-base alloys to steel.

ENiCrFe-2 electrodes are used for welding dissimilar metals and alloys, and for welding the nickel-chromium-

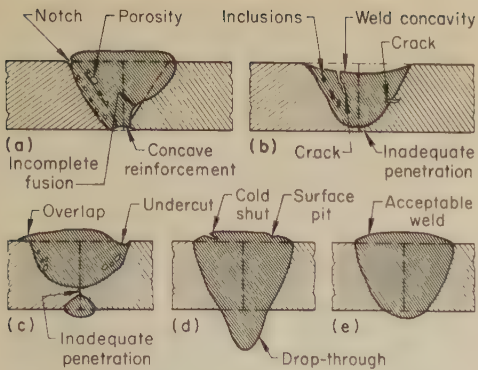


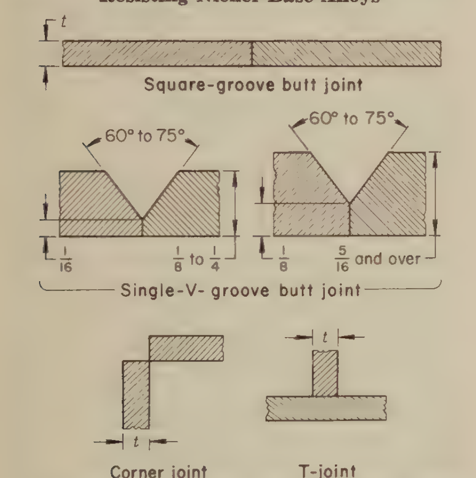
Fig. 10. Typical defects (views a through d) that occur in the arc welding of heat-resisting alloys. View (e) represents a weld with no defects and good reinforcement.

iron alloys to themselves. They are usually preferred for high-temperature applications. ENiCrFe-3 electrodes are not recommended for high-temperature service because they produce a weld metal that has a low stress-rupture strength.

ENiMo electrodes are used for welding the nickel-chromium-molybdenum alloys to themselves and to other metals. These electrodes are normally used only in flat-position welding.

Welding Conditions. Table 7 gives welding conditions for making butt, corner and T-joints in the solid-solution-strengthened nickel-base alloys by shielded metal-arc welding.

Table 7. Conditions for Shielded Metal-Arc Welding of Solid-Solution-Strengthened Heat-Resisting Nickel-Base Alloys



Metal thickness, in.	Number of passes	Current, dcrp(a), amp	Electrode diameter(b), in.
Square-Groove Butt Joints			
1/16	1	40 to 70	3/32
5/64	1	40 to 70	3/32
3/32	2	45 to 75	3/32
Single-V-Groove Butt Joints			
1/8	2	40 to 70	3/32
5/32	2	40 to 70	3/32
3/16	2 to 3	40 to 70	3/32
1/4	3 to 4	40 to 130	3/32 to 5/32
3/8	5 to 6	40 to 130	3/32 to 5/16
1/2	8 to 10	40 to 130	3/32 to 5/16
Corner Joints and T-Joints(c)			
1/16	1	40 to 70	3/32
5/64	1	40 to 70	3/32
3/32	1	40 to 70	3/32
1/8	1	40 to 70	3/32
5/32	1	40 to 100	3/32 to 1/8
3/16	1	40 to 100	3/32 to 1/8
1/4	2	40 to 130	3/32 to 5/32
3/8	3	40 to 130	3/32 to 5/32
1/2	6	40 to 130	3/32 to 5/32

(a) Current should be within the range recommended by the electrode manufacturer. (b) Where a range is shown, the smaller diameters are used for the first pass in the bottom of the groove, and the larger diameters are used for the final passes. (c) Fillet welds.

Causes and Prevention of Weld Defects

Weld defects such as cracks, porosity, inclusions and incomplete fusion usually are unacceptable in weldments made of heat-resisting alloys. Nondestructive inspection is used on almost all completed weldments; destructive inspection generally is limited to test samples. Various types of leak tests are used on weldments that are to be subjected to pressure in service. Thirteen types of defects that occur in arc welds are shown in Fig. 10.

Porosity. Proper cleaning of the joint area to remove surface contamination, interpass cleaning to remove all slag and oxides, and good welding technique will minimize porosity in welds. In Example 275, porosity that resulted from inability to clean the joint adequately was eliminated by a change in the shielding gas. Porosity is also caused by air or other gas being trapped in the weld.

Cracks and Fissures. Cracks are of three general types:

1. Transverse cracks in the base metal perpendicular to the weld
2. Longitudinal cracks in the base metal parallel to the weld
3. Microcracks and macrocracks in the weld metal.

Cracks of any type and size cannot be tolerated. The use of stringer beads helps to avoid cracking by minimizing heat input and weld stress.

Intergranular cracking or fissuring may be caused by grain-boundary segregation, which is likely to be excessive when the impurity content of the base metal is high and when large grains develop in the microstructure because the work metal is held at high temperature or the shielding is inadequate.

Cracking may occur in poorly designed weldments, such as those in which welded joints cross, creating complex, multiaxial stresses in the corner of the weld and an overlapping weld deposit.

In the following example, cracks in the base metal, perpendicular to the weld metal, were caused by shrinkage stress resulting from excessive weld size and high welding current. Oxide formation on the underside of the weld also was objectionable.

Example 280. Minimizing Cracking and Elimination of Oxide Formation in Welding Waspaloy Tubing (Fig. 11)

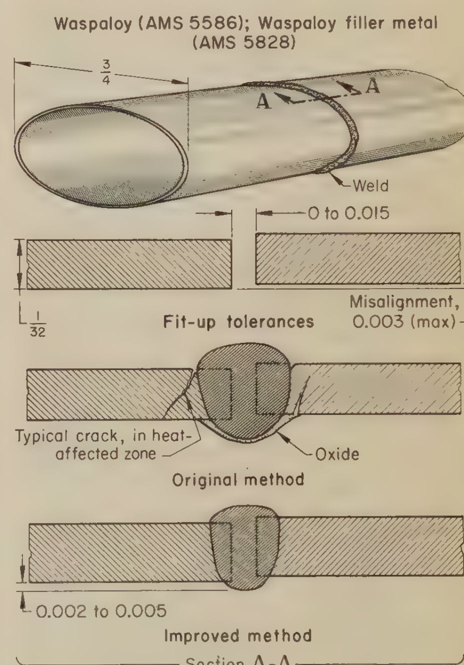
When Waspaloy (AMS 5586) gas-turbine nozzle segments were manual gas tungsten-arc welded, cracking occurred at both root and face sides of the weld in the heat-affected zone, and objectionable oxide formed on the underside of the weld. The parts to be welded were of elliptical shape, the long axis being ¾ in. A typical joint is shown in Fig. 11. Welding had been done carefully, using internal and external argon shielding, and Waspaloy filler metal (AMS 5828). Before welding, joint surfaces were prepared by grinding and cleaned by pressure washing with a detergent solution.

Investigation showed that cracking was directly related to excessive weld size, which had caused high shrinkage stress. A high welding current was responsible for the excessive size of the weld and more root reinforcement than was desirable. Insufficient internal argon pressure also contributed to excessive root reinforcement. Oxidation of the root surface had occurred, air having been pulled into the tube through various openings.

Welding procedures were changed as follows: current was reduced from 30 to 18 amp, and backing gas pressure and purity were increased by increasing the flow rate from 8 to 15 cu ft per hour and by taping all openings except a small exit port. As a result, root reinforcement was reduced to 0.002 to 0.005 in., and the smaller weld deposit and the lower heat input reduced shrinkage stresses so that rejections for cracking were decreased by 80%. Oxidation of the root surface was prevented.

Welding conditions are given in the table that accompanies Fig. 11. After welding, joints were inspected visually and radiographically, and then were tested at 100-psi hydrostatic pressure. Reducing the number of rejects by 80% represented the greatest improvement that had been made in 11 years of welding this heat-resisting alloy.

Strain-age cracking can occur in precipitation-hardenable nickel-base al-



Welding Conditions for the Improved Method

Joint type	Butt
Weld type	Square groove
Welding process	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier, with gas-and-water time delay, high-frequency and remote current control
Electrode	1/16-in.-diam EWTh-2, tapered to 0.002 to 0.006-in. diameter
Torch	200 amp, water cooled, with gas lens
Filler metal	0.031-in.-diam Waspaloy
Shielding gas, at torch	Argon, at 18 cfh
Backing gas	Argon, at 15 cfh
Welding position	Flat
Fixtures	Holding clamp
Current	18 amp, dcsp
Voltage	15 to 20 v
Arc starting	High frequency
Arc length	1/8 in. (approx)
Number of passes	One

Fig. 11. Waspaloy nozzle segment, and joints welded by original and improved methods, showing size of weld and location of cracks (Example 280)

loys during the initial heat treatment after welding if the metal welded is in the aged condition and at least one area, such as the as-deposited weld metal, is in the solution-treated condition. Cracks that form under these conditions are relatively large, most of a crack being in the base metal. The metal is more likely to crack when an aged part is being repair welded. To minimize strain-age cracking, the following precautions should be taken:

1 Weld in the solution-treated (annealed) condition.
2 Weld with minimum restraint.
3 Do not preheat for welding.
4 Use as little heat input as possible.
5 Accomplish postweld solution heat treatment by heating as rapidly as possible through the aging temperature range.

Test data relating to René 41 exclusively indicate that overaging this alloy prior to welding is useful in avoiding strain-age cracking (see the discussion "Overaging René 41", on page 282).

Cold shuts and surface pits in a weld are possible evidence of a subsurface crack or of porosity that has emerged to the surface. Also, there may be lack of fusion between successive layers of weld metal or between adjacent weld beads. Cold shuts can occur between the weld metal and the base metal when hot metal runs ahead onto a cold metal surface and does not fuse properly. Cold shuts should be removed by grinding because they are possible sources of stress corrosion. Both visual and dye-penetrant inspection are used to locate cold shuts and surface pits.

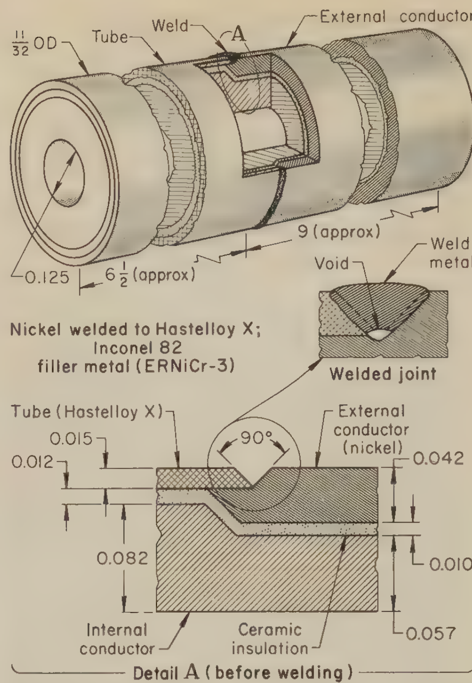
Voids in welds can occur when air has been trapped in a groove or between two pieces of metal being welded. When welding a lining in a thick-wall vessel or when welding one tube inside another, entrapped air can cause a void if it does not have an easy escape path.

In the following example, a void occurred when two tubes of different wall thickness but the same outside diameter were welded together. The thick-wall tube was machined to fit inside the thin-wall tube.

Example 281. Elimination of a Void at the Root of a Joint (Fig. 12)

The elimination of a small tear caused by a small void at the root of a welded joint presented a problem in making the laminated resistance heating element shown in Fig. 12. A thin-wall Hastelloy X tube of high electrical resistance was welded to a heavier, pure nickel conductor tube. An inner tube, also of pure nickel, was separated from the outer tube by a layer of ceramic insulation, and completed an electrical circuit when joined to the Hastelloy X tube at the heater end. After welding, the weld metal was machined flush and the tube assembly was swaged to shape.

A small tear occurred in the weld metal after swaging, at the point on the circumference where the final joint closure was made. A small void found at the root of the joint was assumed to have weakened the weld sufficiently to cause the small rupture. It was concluded that the void was caused by a small amount of air (under pressure) trapped at the root of the joint. During welding, the air expanded and found an easy escape path through the unwelded portion of the joint, until the closure was made and the escape path was sealed off. There was no alternate route along the tube interlayers because of the close fit of components.



Joint type	Butt
Weld type	Single-V groove with backing
Welding process	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier
Electrode holder	250 amp, water cooled
Electrode	1/16-in.-diam EWTh-2
Filler metal	1/32-in.-diam Inconel 82 (ERNiCr-3)
Shielding gas	Argon
Welding position	Horizontal-rolled pipe
Current	15 amp, dcsp
Voltage	15 v
Arc starting	High frequency
Number of passes	One
Edge preparation	Machining (see text)
Special equipment	Vacuum pump

Fig. 12. Joint between resistance and conduction segments of a laminated, tubular resistance-heating element, location of void at root of weld, and joint design (Example 281)

To ensure evacuation of the tube, a small vacuum pump was connected to one end of the tube and the other end of the tube was sealed with a rubber stopper, leaving a path for escape of air through the interlayers. Pumping to obtain a low vacuum was carried out before and during welding. The tube was rotated manually during welding. The vacuum hose was long enough to be twisted through 360° of rotation without significant loss of vacuum. Using this procedure, no more tears occurred, and the problem was solved.

After swaging, the welded joints were tested by a helium mass spectrometer. The vacuum was applied to the end of the tube (as in welding) and helium test gas to the outside of the tube at the weld.

Inconel 82 (ERNiCr-3) filler metal was selected for this dissimilar-metal joint because of its strength and excellent ductility in the as-welded condition. Joint design consisted of a 90° single-V groove formed by beveling the 0.015-in.-wall Hastelloy X tube 45° and the 0.042-in.-wall nickel tube 45° to a depth of 0.015 in., which ensured a nickel backing for the joint (Fig. 12). The tubes were machined and washed in acetone before assembly for welding.

Manual gas tungsten-arc welding with argon shielding gas was used to deposit the weld metal in a single pass. No preheat was needed. Details of the welding procedure are summarized in the table that accompanies Fig. 12.

Notches are formed when the edge of the weld reinforcement is thick and does not blend smoothly into the surface of the base metal (see Fig. 10). Frequently, the edge of the reinforcement can be ground or machined to obtain suitable blending, but preferably welding practice should be changed to prevent the condition.

Iron-Nickel-Chromium and Iron-Chromium-Nickel Heat-Resisting Alloys

These iron-base heat-resisting alloys include strain-hardenable, solid-solution-strengthened, and precipitation-hardenable types. All contain appreciable amounts of nickel and chromium, with either one or the other of these elements constituting the principal alloying addition. Other alloying elements are generally added to increase hot strength (molybdenum, tungsten and cobalt), to act as stabilizers (columbium and tantalum), or to promote strengthening (aluminum, titanium, copper and boron).

The usual range of service temperature for these alloys (1200 to 1400 F) limits the selection of filler metals and preheat and postheat treatments for welding. Nominal compositions of the common Fe-Ni-Cr and Fe-Cr-Ni heat-resisting alloys are given in Table 1.

The 16-25-6 and 19-9 DL alloys are strain-hardenable and are easily joined by arc welding. Weld deposits can be made with an austenitic stainless steel filler metal, with a nickel-base alloy filler metal, and with a filler metal of the same composition as the base metal. Generally, preheating and postheating are used.

The solid-solution-strengthened alloys, such as N-155, are easily welded by the shielded metal-arc, gas metal-arc, and gas tungsten-arc processes; however, the heat input should be kept low, and the welds should be cooled rapidly to maintain weld ductility.

Some precipitation-hardenable alloys, such as A-286, are considerably more difficult to weld. These alloys are extremely sensitive to intergranular hot cracking in the weld metal and in the heat-affected zone. Cracking is most likely to occur when aged metal or highly restrained parts are joined. Cracks in root passes or crater cracks can be minimized by using suitable welding procedures and techniques to control heat input during welding. Microcracking (microfissuring) can occur in the weld metal and in the heat-affected zone and must be controlled by proper preweld and postweld heat treatment and by selection of the most suitable filler metal.

Nevertheless, high joint efficiency can be obtained in arc welding A-286 sheet up to 0.094 in. thick. Joints in thicker sections are more difficult to weld and require special techniques such as automatic welding, a single pass, or the use of weld back cooling.

In all the precipitation-hardenable alloys, the aluminum, columbium or titanium may combine with either the iron or the major solid-solution elements to form a low-melting eutectic phase in the grain boundaries. Melting of this grain-boundary phase, often called incipient melting, occurs at the fusion line during welding, and thermal stresses incidental to weld cooling

cause the grains to separate. Grain separation produces gross subsurface cracks or microfissures which are difficult to detect by available nondestructive inspection methods.

Joint design for iron-base heat-resisting alloys depends on the welding process, the application, and the filler metal used. For some applications, joint designs similar to those used for stainless steels are appropriate (see Table 4 in the article on Arc Welding of Stainless Steel); for other applications, joint designs similar to those shown for nickel-base alloys are used (Table 3 here), except that the included angle of V-grooves is usually 60° — for shielded metal-arc welding, it may be from 75° to 90°. Although square-groove butt joints are usually used for metal up to ⅛ in. thick, in Example 282, a zero-root-face V-groove was ground in 0.080-in.-thick A-286 sections. Because nickel-base alloys have low fluidity, wider joint bevels and openings are sometimes required when welding with nickel-base filler metal.

Preweld and Postweld Heat Treatment. The strain-hardenable alloys usually are welded in the hot-cold worked condition. The metal in the heat-affected zone is essentially solution treated by the welding heat, resulting in a decrease in hardness and strength. Although the strain-hardenable alloys frequently are preheated for welding, the preweld heat treatments must be done in a limited temperature range to avoid annealing the metal. This same restriction on heat treating temperature applies to postweld treatments of these alloys.

The solid-solution-strengthened alloys generally are welded in the solution-treated condition and are used without postweld heat treatment. These alloys have a small zone of grain growth adjacent to the weld, but this does not appreciably reduce weld strength.

The precipitation-hardenable alloys are welded in the solution-treated condition because the greater ductility of the base metal in this condition permits some relaxation of the shrinkage stresses associated with welding. Postweld heat treatment generally includes a re-solution treatment and an aging treatment.

Gas Tungsten-Arc Welding of Iron-Nickel-Chromium and Iron-Chromium-Nickel Alloys

Gas tungsten-arc welding is the most widely used process for joining Fe-Ni-Cr and Fe-Cr-Ni heat-resisting alloys, especially in thin sections, because the welding operation can be observed and controlled easily and because of the high percentage of alloy transfer that is characteristic of the process. The minimum heat input that is appropriate to work-metal thickness and to filler-wire diameter should be used, to reduce the temperature gradient in the heat-affected zone. The amount of heat input is particularly important in welding of the precipitation-hardenable alloys, because these alloys are subject to grain-boundary melting.

Straight-polarity direct current is used for welding the Fe-Ni-Cr and Fe-Cr-Ni alloys. Thoriated tungsten electrodes (EWTh-2) are most commonly employed.

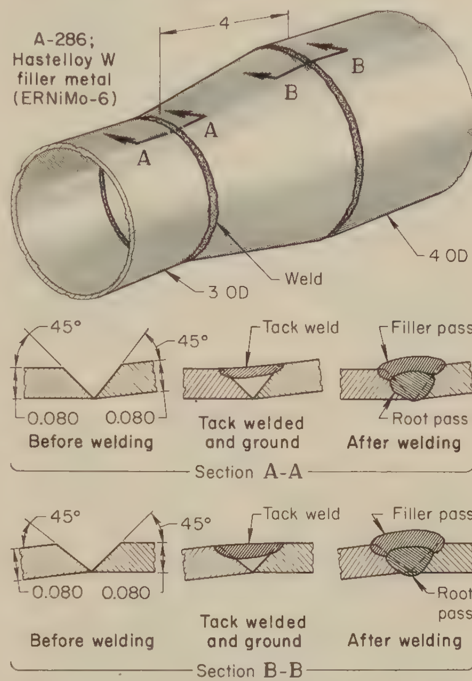
Conditions for manual gas tungsten-arc welding of A-286 and Incoloy 800 are given in Table 8.

Argon shielding gas at a flow rate of 15 to 20 cu ft per hour is used at the torch. Argon is also used for purging before welding and as a backing gas.

If shielding is inadequate, aluminum and titanium, which are present in the precipitation-hardenable alloys, are likely to combine with oxygen in the air to form refractory oxides on the surface of the weld bead being deposited. These oxides may result in oxide inclusions or otherwise interfere in the production of a sound weld. In multiple-pass welding, surface oxides must therefore be removed after each welding pass, preferably by grinding.

Filler metals that will produce weld metal with a composition that is the same as, or similar to, that of the base metal are usually selected. Wire of the same composition as the base metal, austenitic stainless steel wire, and nickel-base alloy wire are used (see Table 6). Because the heat-resisting alloys have relatively high strength at elevated temperature, the solidifying weld metal frequently is severely stressed. Hastelloy W (ERNiMo-6), a nickel-base filler metal that has good hot strength and sufficient ductility to prevent cracking during weld solidification, is recommended for joining many of the Fe-Ni-Cr and Fe-Cr-Ni alloys. This filler metal is not age hardenable, but its as-welded mechanical properties are satisfactory for many applications. For high-stress applications of the precipitation-hardenable iron-base alloys, a filler metal that responds to age hardening, and thus develops the highest joint efficiency, is recommended.

Production Example. Procedures for gas tungsten-arc welding of thin workpieces of a precipitation-hardenable alloy are described in the following example. Filler metal, joint preparation, method of purging the weld, and welding technique were carefully selected to prevent weld or base-metal cracking.



Joint type	Butt
Weld type	Single-V groove (see figure)
Welding process	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier, with high-frequency arc starting and automatic time delay for gas and water
Electrode	$\frac{1}{16}$-in.-diam EWTh-2, tapered to a sharp point
Torch	Water cooled
Filler metal	$\frac{1}{16}$-in.-diam Hastelloy W
Shielding gas:	
At torch	Argon, 10 to 15 cfh
Backing gas	Argon, at 10 cfh
Welding position	Horizontal-rolled pipe position
Fixtures	V-block; turning rolls
Current	70 amp, max, dcsp(a)
Voltage	Not controlled
Arc starting	High frequency

(a) Foot-operated remote control was connected with low-range circuit of power supply.

Fig. 13. Gas tungsten-arc welded A-286 fuel duct for which special welding techniques were used to prevent cracking (Example 282)

Example 282. Welding Procedures That Prevented Cracks in A-286 Aerospace Fuel Ducts (Fig. 13)

Special techniques were needed to weld sections of A-286 fuel ducts to meet radiographic inspection requirements. The chief concern in welding this alloy was to prevent cracking, which was likely to occur in the weld metal, in the underbead region, and in the heat-affected zone.

The reducing section (Fig. 13) was welded to the two straight-side tube sections in two passes for each weld, using manual gas tungsten-arc welding, Hastelloy W (ERNiMo-6) filler metal, and argon gas for external and internal shielding. The welding conditions are summarized in the table that accompanies Fig. 13.

Material Condition. The components were welded in the solution-treated condition. If a part was cold worked after solution treatment, it was re-solution treated before welding.

Joint Preparation and Fit-up. Section ends were beveled 45° to a featheredge

Table 8. Conditions for Manual Gas Tungsten-Arc Welding of 0.062-In.-Thick Alloy A-286 and Incoloy 800

Item	Alloy A-286	Incoloy 800
Joint type	Square butt(a)	Square butt(a)
Electrode	$\frac{3}{32}$-in.-diam EWTh-2(b)	$\frac{3}{32}$-in.-diam EWTh-2(b)
Filler metal	0.062-in.-diam Hastelloy W (ERNiMo-6)	0.062-in.-diam ERNiCrFe-5
Number of passes	One	One
Welding speed, ipm	2 to 3	2 to 4
Current (dcsp), amp	70 to 85	65 to 80
Voltage, v	10 to 12	10 to 12
Arc starting	High frequency	High frequency
Shielding gas:		
At torch	Argon, at 15 to 20 cfh	Argon, at 15 to 20 cfh
Backing gas	Argon, at 5 to 10 cfh	Argon, at 5 to 10 cfh
Preheat and postheat	None	None

(a) Zero root opening for welds from ¼ to 2 in. long; $\frac{1}{32}$ to $\frac{3}{64}$-in. root opening for welds from 2 to 4 in. long. (b) Electrode tapered to $\frac{1}{64}$-in. diameter.

(zero root face) by grinding and disk sanding (see Fig. 13). Extreme care was needed to prevent burning or overheating of the featheredges.

Sections to be joined were vapor degreased. After fit-up, and just before welding, joints were again cleaned, using a stainless steel wire brush. Accuracy of fit-up was important: overlaps, misalignment, and root openings were not permitted.

Filler Metal. Hastelloy W filler-metal wire was used for tack and groove welding, in preference to A-286 filler-metal wire, because deposition proceeded more smoothly, with less drop-through and better wetting of the groove faces; the incidence of cracking in the weld metal (as detected by dye-penetrant inspection) was lower, and the Hastelloy W wire was easier to handle.

Tack Welding. During fit-up, tack welds were placed at ½-in. intervals around the joint, each tack being carefully deposited across the top of the groove instead of at the root. This procedure (contrary to normal practice) was necessary to avoid oxidizing or overheating the root of the joint; internal gas purging was not used during tack welding, except when fit-up at the featheredge was poor, leaving a small gap. The tack welds were ground flush with the tube wall, leaving a thin web of tack-weld metal, which was consumed during the intermittent root pass. For tack welding and for the initial welding pass, the parts were supported in a V-block.

Argon Purging. After tack welding, purging dams fitted with small-diameter pipe fittings were placed at both ends of the assembly. A hose attached to one dam provided an argon flow of 10 cu ft per hour. In the dam at the opposite end, an exit orifice was made by placing adhesive masking tape over the fitting and puncturing the tape with a 3/32-in.-diam electrode.

Welding. The root pass was made by depositing intermittent welds 1 to 1¼ in. long separated by intervals of about the same length. Each end of the weld bead was then ground back approximately ⅛ in. to a featheredge, using a small grinder fitted with a 1-in.-diam by 1/32-in.-thick wheel. When the joint was cool enough to handle with bare hands, the root pass was completed by filling the intervals.

Intermittent welding was used during the root pass to reduce heat input and cumulative shrinkage stress. The ends of the weld beads were ground to remove possible cracks at these stress points and to reduce heat buildup on making the tie-ins.

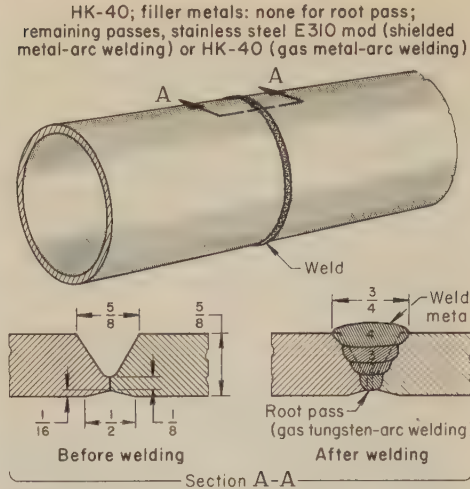
During welding, current was regulated by a foot-operated remote control switch that was connected with the low-range circuit of the power supply. A low welding current (70 amp, max) was used because excessive heat would have caused cracking.

After it was cooled to room temperature, the root bead was cleaned with a power-operated stainless steel wire brush and inspected visually and by a dye-penetrant method for cracks, especially at tie-in points. Cracks were removed by grinding, and the areas to be repaired were blended in before being carefully rewelded.

The second (filler) pass was made while the duct was being rotated on turning rolls. This prevented heat buildup, which was likely to occur if the operator had to stop to turn the workpiece during welding. Stops and starts caused root cracking that was not detectable by dye-penetrant inspection but that was evident in radiographs. If the duct could not be automatically rotated, the second pass was made by intermittent welding.

Gas Metal-Arc Welding of Iron-Nickel-Chromium and Iron-Chromium-Nickel Alloys

Gas metal-arc welding is sometimes used for these heat-resisting alloys when sections are more than about ½ in. thick, where joint design and work-



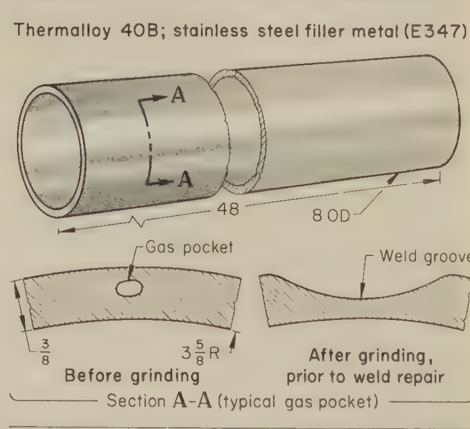
Joint type	Circumferential butt	
Weld type	Modified single-U groove	
Welding position	Horizontal-rolled pipe	
Root Pass		
Welding process	Manual gas tungsten-arc	
Electrode	3/32-in.-diam EWTh-2	
Filler wire	None	
Shielding gas	Argon, at 20 cfh	
Current	120 amp, dcsp	
Voltage	26 v	
Welding speed	2 ipm	
Buildup Passes	Original method	Improved method
Welding process	Shielded metal-arc	Gas metal-arc(a)
Electrode	Mod E310(b)	HK-40 wire
Electrode diam, in.	5/32	0.045
Shielding gas	...	Argon-CO_2
Current, amp	130, dcrp	...
Voltage, v	28	...
Welding speed, ipm	0.5	...

(a) Automatic. (b) 0.35 to 0.45% carbon.

Fig. 14. Cast HK-40 alloy tubing that was welded by gas tungsten-arc welding for the root pass and automatic gas metal-arc welding for the filler passes, and joint design, and sequence of passes (Example 283)

piece size can compensate for the high heat input. In general, it is not recommended for wrought heat-resisting alloys, but it is used for castings.

Electrode material is selected to match the composition of the base metal and to suit service conditions.



Revised Welding Conditions

Weld type	Repair
Welding process	Shielded metal-arc
Power supply	400-amp transformer-rectifier
Electrode	⅛-in.-diam E347-16
Current	100 amp, dcrp
Voltage	32 v
Preheat and postheat	None

Fig. 15. Cast Thermalloy 40B calcining tube, and preparations for weld repair of gas pocket (Example 284)

The following example describes an application in which gas metal-arc welding was used to build up a weld after the root pass had been deposited by gas tungsten-arc welding.

Example 283. Use of Gas Metal-Arc Welding for Filler Passes on a Circumferential Joint in ⅝-In.-Wall Cast Tubing (Fig. 14)

The ⅝-in.-wall tubing shown in Fig. 14 was originally joined by gas tungsten-arc welding for the root pass and shielded metal-arc welding for the filler passes. This practice was changed so that filler passes were welded by the automatic gas metal-arc process, because it was faster and offered improved control. In addition, wire brushing and grinding after each pass were eliminated, and less skill was needed.

The HK-40 tubing (25% chromium, 20% nickel, 0.35 to 0.45% carbon) was beveled as shown in Fig. 14, section A-A. A gas tungsten-arc root pass without filler metal gave a smooth, continuous weld bead on the inaccessible interior of the circumferential joint and provided a sound surface for the weld that was made from the other side. As a result, visual inspection, using a boroscope, was easily accomplished and interpretation of radiographs was simplified, compared with a weld in which a backing strip was used.

The filler passes were made with automatic gas metal-arc welding. Weld metal was deposited by a modified weaving technique to ensure uniform deposition across the groove, low residual stresses in the weld metal, and rapid weld-metal deposition. The final bead extended 1/16 in. beyond the edge of the weld groove.

The root bead and the final bead were inspected for surface discontinuities by the dye-penetrant method. Welded joints were examined radiographically in accordance with paragraph UW-51, Section VIII, ASME Boiler and Pressure Vessel Code, except that 10% random sampling was used.

Shielded Metal-Arc Welding of Iron-Nickel-Chromium and Iron-Chromium-Nickel Alloys

Shielded metal-arc welding can be used for joining Fe-Ni-Cr and Fe-Cr-Ni heat-resisting alloys when gas tungsten-arc welding equipment is not available or when it is not practical to use the gas tungsten-arc process.

Reverse-polarity direct current produces the best mechanical properties in the welds. When joint design permits, rapid travel with as little weaving as possible is preferred, to minimize heat input. To avoid overheating when starting and when stopping a weld, welding currents that are consistent with the metal thickness or the size of the components should be used. Striking the arc on a starting tab adjacent to the joint will help prevent cracking at the beginning of the weld bead. The arc can be broken on a similar tab at the end of the weld, but doubling back on the bead with a slant arc is also acceptable. Whenever possible, welding should be done in the flat position.

Electrodes for shielded metal-arc welding usually are selected so that the composition of the deposited weld metal is close to that of the base metal. Service requirements, such as operating temperature or the need for crack-free weld metal, often influence selection of electrode metal. For example, for applications in which service temperature is above 1650 F, welding electrode Inconel 112 is recommended

for joining Incoloy 800. For applications in which service temperature is below 1650 F, welding electrode Inco-Weld A (ENiCrFe-2) is recommended. When service temperature is below 1000 F and the weld metal must meet stringent fissure specifications, Inconel 182 (ENiCrFe-3) is recommended.

The compositions of electrodes used for welding Fe-Ni-Cr and Fe-Cr-Ni heat-resisting alloys appear in Table 6.

Production Example. Repair of casting defects is a typical application of shielded metal-arc welding. In the following example, the base metal, the electrode material, and the preheating practice were carefully evaluated to assure satisfactory results.

Example 284. Change in Welding Procedure To Avoid Intergranular Corrosion in Cast Thermalloy 40B Tubes (Fig. 15)

X-ray inspection showed scattered gas pockets in cast tubes of Thermalloy 40B, and repair welding was required. The tubes, used in a calciner that operated at 1400 F to convert uranyl nitrate to uranium oxide, were 8 in. in outside diameter, with a ⅜-in. wall, and 48 in. long.

Because of a misunderstanding as to alloy composition, the first repair welding procedure attempted resulted in carbide precipitation in the grain boundaries and failure of the welded areas by intergranular corrosion within three months. The original repair procedure was as follows: The defective tubes were cleaned in hot trichlorethylene vapor and rinsed in hot water, and the defects were ground out, using a hand grinder. Before welding, the tubes were furnace heated to 600 F, and around each defect, an area about 4 in. in diameter was heated to 1100 F with a torch. The defects were repaired by shielded metal-arc welding, using a ⅛-in.-diam austenitic stainless steel electrode, E309-16, and a welding current of 100 amp (dcrp). The tubes were then wrapped in an asbestos blanket to obtain slow cooling.

Because of the poor performance as a result of the first welding procedure, a new procedure was tried. Tubes were cleaned for welding in the same manner as before, preheating was eliminated, a columbium-tantalum-stabilized stainless steel electrode, E347-16, was used, and the tubes were cooled in air after welding. Elimination of the high preheat and the slow cooling reduced carbide precipitation in the heat-affected zone of the base metal, although the higher rate of cooling did cause some cracking. The columbium-tantalum-stabilized electrode also inhibited carbide precipitation in the weld. Although tubes failed from intergranular corrosion after approximately three years of service, the failures were not associated with the weld repairs.

Details of the revised welding procedure are given in the table with Fig. 15.

Submerged-Arc Welding of Iron-Nickel-Chromium and Iron-Chromium-Nickel Alloys

Submerged-arc welding of these heat-resisting alloys normally is limited to applications involving thick sections, where high deposition rate is desired. For some alloys, the lack of a suitable flux prevents the use of this process.

The types of joints and groove designs are similar to those used for submerged-arc welding of low-carbon steel. The composition of the weld metal is often critical when joining Fe-Ni-Cr and Fe-Cr-Ni heat-resisting alloys, and so careful selection of the electrode and of the flux is needed. The electrode is generally of a composition that will produce weld metal of the same composition as the base metal. Modified stainless steel electrodes are used for welding castings. Hastelloy W (ERNiMo-6) can be used where joint strength is not a critical requirement and a weld metal of good ductility is needed.

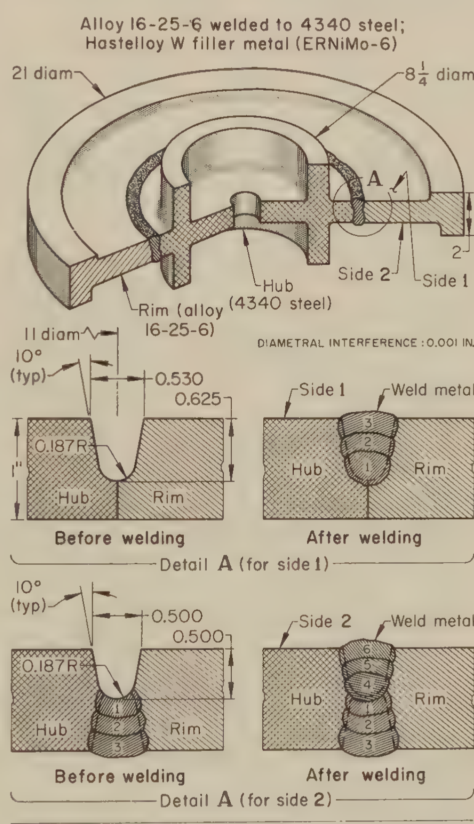
Production Example. In the following example, submerged-arc welding was used for joining a strain-hardenable alloy to an alloy steel. Filler metal, groove design, preheating, and postweld heat treatment were selected to preserve the mechanical properties of both alloys.

Example 285. Joining Heat-Resisting 16-25-6 Alloy to 4340 Steel in Gas-Turbine Wheels (Fig. 16)

Turbine wheels for aircraft gas-turbine engines had a 4340 steel hub and a 16-25-6 alloy rim that were joined by welding, as shown in Fig. 16. Submerged-arc welding was selected for the 1-in.-thick joint because of its high deposition rate and the consistent weld quality obtainable.

A 3⁄16-in.-diam electrode wire made of Hastelloy W (ERNiMo-6) was selected for filler metal, because of its good weld-crack resistance in joining dissimilar metals. The tabulation that follows shows how its composition compares with that of 16-25-6 alloy and 4340 steel:

Element	16-25-6 (rim)	Hastelloy W (filler metal)	4340 (hub)
Carbon	0.07	0.12	0.41
Manganese	2.00 max	1.00 max	0.75
Silicon	1.00 max	1.00 max	0.27
Chromium	16.00	5.00	0.80
Cobalt	...	2.50 max	...
Molybdenum	6.00	24.5	0.25
Nickel	25.00	Rem	1.80
Vanadium	...	0.60	
Phosphorus	0.030	0.040	0.015
Sulfur	0.030	0.030	0.015
Nitrogen	0.15	...	...
Copper	0.50	...	...
Iron	Rem	5.50	Rem



Joint type	Butt
Weld type	Double-U groove(a)
Welding process	Submerged-arc
Power supply	1000-amp transformer
Electrode	3⁄16-in.-diam Hastelloy W (ERNiMo-6)
Flux	Neutral
Current	518 amp, ac (all passes)
Voltage	28 to 35 v (all passes)
Stickout	1¼ in.
Travel speed	13.3 ipm (all passes)
Wire feed	Automatically controlled
Fixture	Turntable

(a) The first U-groove was filled with weld metal before the second groove was cut.

Fig. 16. Section through a bimetal gas-turbine wheel showing location of weld joining the two alloys, joint design, and sequence of operations in groove cutting and weld-metal deposition (Example 285)

Before welding, the 16-25-6 rim was conditioned for optimum strength by hot-cold working at 1260 F during the final forging operation. (Because of this treatment, subsequent heat treatment of the weldment was limited to 1200 F max.) Rim hardness was Rockwell C 22 to 30.

The 4340 steel hub was quenched and tempered to a hardness range of Rockwell C 26 to 32.

Although the butt joint was designed for what ultimately became a double-U-groove weld, as shown in Fig. 16 (detail A for side 1), the groove on the first side was completely welded before the groove on the second side was cut.

The rim and hub were machined for a shrink fit, and mating edges of the side that was to be welded first were beveled, degreased and wiped with acetone. After furnace preheating the rim to 850 F and the hub to 650 F, the two parts were assembled and mounted for flat-position welding on a rotating positioner, with a circular gas burner located under the joint for preheat control. The parts were dimensioned for diametral interference of 0.001 in. at room temperature. This permitted assembly with an easy sliding fit after furnace preheating, and gave a light interference fit after the temperature became equalized at 550 F.

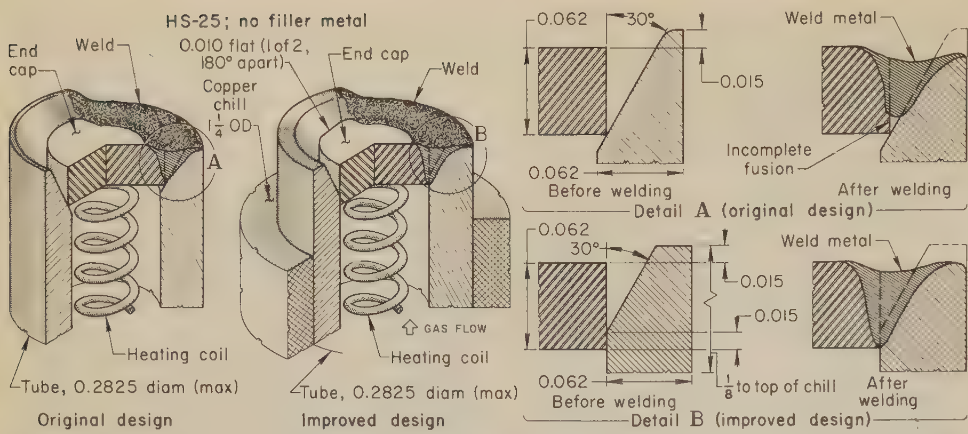
After the first-pass bead was deposited, using the settings shown in the table that accompanies Fig. 16, the weld metal was cleaned of slag and wire brushed. Interpass temperature was adjusted to 575 F. Passes 2 and 3 were deposited using the same settings as for the first pass. The part was immediately transferred to a furnace at 600 F, heated to 1065 F (at a maximum rate of 100 F per hour), held for 6 hr, furnace cooled to 500 F (at a maximum rate of 100 F per hour), removed from the furnace, and air cooled.

A groove was then cut on the second side to be welded (Fig. 16, detail A for side 2). The part was preheated in a furnace to 650 F, transferred to the welding positioner, temperature equalized at 550 F, and welding was completed using the same technique as before. Immediately after the final pass, the part was placed in a furnace at 600 F and held for 4 hr; the remainder of the postweld heat treatment was the same as for the weld on the first side.

After machining off 1⁄32 in. of weld metal and across the base metal in the weld area, the joint was inspected by radiographic, magnetic particle, and fluorescent-penetrant techniques. Hardness surveys taken across the joint were as follows:

4340 hub base metal	28 Rc
4340 heat-affected zone	24 to 25 Rc
Hastelloy W weld metal	20 to 24 Rc
16-25-6 heat-affected zone	20 to 22 Rc
16-25-6 rim base metal	25 to 26 Rc

Joint tensile strength averaged 113,000 psi; yield strength, 68,000 psi; elongation in 2 in., 9%; and reduction of area, 16%. Failure in tests occurred in the weld metal. In addition to helping to preserve mechanical properties of the base metals, the preheat and the heat treating cycles were successful in preventing the formation of untempered martensite in the heat-affected zone of the 4340 hub, thus eliminating this potential source of cracking.



Joint type	Corner
Weld type	Single-bevel groove
Welding process	Automatic gas tungsten-arc
Power supply	200-amp, dc motor-generator
Electrode	0.040-in.-diam EWTh-2, tapered to 0.015-in. diameter
Torch	110 amp, air cooled
Filler metal	None
Welding position	Flat

Current	45 amp, dcsp
Shielding gas:	
At torch	Argon, at 20 cfh
Backing gas	Argon, at 2 cfh
Fixtures:	
Workpiece	Copper chill ring, turntable mounting
Torch	Clamped to swing-arm mount
Arc starting	High frequency
Arc length	1/16 in.
Production rate	65 pieces per hour

Fig. 17. End-closure detail of sheathed heating-element assembly, and original and revised joint design (Example 286)

Cobalt-Base Heat-Resisting Alloys

Cobalt-base heat-resisting alloys (see Table 1) are available in both cast and wrought forms. Generally, the cast alloys are more difficult to weld than are the wrought alloys but, other than repair welding, there is little need to weld most such castings.

Where the application requires very high reliability of welds, only gas tungsten-arc and gas metal-arc welding are recommended; otherwise, shielded metal-arc welding is used.

Joint design and weld grooves for the cobalt-base alloys are essentially the same as for the nickel-base alloys (see Table 3).

A square-groove butt joint is used for sheet metal up to about 7/64 or 1/8 in. thick, a V-groove for plate up to 3/8 in. thick, a double-V groove or a double-U groove for thicknesses of 3/8 to 5/8 in., and a double-U groove for thicknesses over 5/8 in. Where T-joints are used, the same groove limitations apply as for butt joints. Corner-joint welds should be backed by a fillet weld if possible. This type of joint should be avoided where high stresses are likely to occur.

V-grooves should have a 60° groove angle for gas tungsten-arc welding.

The weld grooves should be machined to assure proper fit-up. The edges of a sheared plate should be ground or machined back 1/16 in. to remove stressed metal. Gas and arc cutting and beveling are not recommended.

All joints should be designed to ensure full penetration. In the following example, improved joint design and use of argon backing gas resulted in 100% penetration and prevented oxide formation at the root of a joint.

Example 286. Changes in Joint Design, Shielding, and Heat Extraction That Eliminated Defects in Welds in HS-25 (Fig. 17)

The end closure for a sheathed heating-element assembly required welding a disk-shape HS-25 end-cap stamping to the open end of a 0.2825-in.-diam HS-25 tubular sheath (Fig. 17). Earlier, the end cap had been welded to a wire coil that served as the heating element of the assembly. After the end cap was welded on, the tube was packed with ceramic insulation material, and swaged to reduce the diameter approximately 16%, thus compacting the insulation. Tests were made for leaktightness and for electrical properties.

The original welding procedure consisted of fitting the end cap with its welded-on heating coil into the beveled end of the tube as shown in Fig. 17, original design and detail A. Then the tube was mounted vertically on a turntable and rotated under a fixed gas tungsten-arc torch. The shielding gas was argon. Weld metal was obtained by melting down the protruding tube wall.

The customer's specification of 100% joint penetration (with a joint design not conducive to complete penetration) required the use of excessive heat, which being conducted to the heating coil attached to the end cap, caused the joint between the heating coil and the end cap to become softened and to fail during the swaging and assembly operations that followed. A second defect was the formation of oxides (because of inadequate shielding and trapped air) on the interior of the tube and at the root of the joint. The oxides that formed on the inside of the tube caused short circuiting during final testing and those at the root of the joint caused incomplete fusion. To eliminate these conditions, a new procedure was developed, which is described below.

First, the depth of the bevel on the tube was reduced to provide a root face of 0.015 in. (see detail B in Fig. 17), and the diameter of the end cap was decreased to provide a press fit into the tube. Two flats were ground on the end cap to allow the escape of air and thus permit the use of argon gas for shielding the back of the weld. An O-ring that held the tube in the rotating fixture also served as a seal for the argon backing gas, which flowed through the rotating fixture and into the tube. This procedure was successful in preventing oxide formation on the inside of the tube and at the weld root, but new difficulties developed: the heat produced by welding caused the O-ring to break down and the end cap to become overheated. Both of these difficulties were corrected by placing a copper ring on the tube to act as a heat sink.

The sequence of operations finally adopted was as follows:

1 Degrease parts; solution heat treat the tube under vacuum, which also cleaned the tube.
2 Press fit end cap assembly into tube.
3 Mount tube in rotatable fixture.
4 Place copper heat sink around tube.
5 Purge air from tube interior with continuous flow of argon.
6 Move swing-mounted torch into position (1/16 in. above, and centered on, tube wall).
7 Start gas flow, arc and turntable rotation. After two weld passes, terminate arc, rotation and gas flow in half a rotation.
8 Retract torch, unclamp heat sink, and remove assembly with a special hand tool.
9 Test assembly for leaks by holding under water for 10 sec while pressurized with air at 100 psi.

This procedure produced 100% joint penetration when used with the welding conditions given in the table that accompanies Fig. 17. Rejects after swaging amounted to less than 1%, compared with more than 20% previously. Electrodes were changed two or three times during an 8-hr shift, because the points became misshaped. After each electrode change, the first piece welded was sectioned and polished to check for penetration and defects.

Cleaning. The weld joint and the adjacent area must be thoroughly cleaned before welding. All foreign matter should be removed by grinding, machining or scrubbing with a suitable solvent. Shot or sand blasting should not be used because iron and sand particles embedded in the work-metal surface can cause serious contamination. Wire brushing should be done with stainless steel or copper brushes; carbon steel brushes can contaminate the base metal.

If the alloys are heat treated in an oil-fired furnace, fuels of low sulfur content must be used to avoid sulfur contamination and subsequent detrimental effect on mechanical properties and corrosion resistance.

Gas Tungsten-Arc Welding. Straight-polarity direct current is preferred for gas tungsten-arc welding of cobalt-base alloys. A thoriated tungsten electrode (EWTh-2) of the smallest diameter that will carry adequate current is recommended. Use of electrodes too small in diameter, at high current densities, can cause excessive electrode erosion and result in tungsten inclusions in the weld metal.

To ensure sound welds, argon gas at a flow rate of 15 to 25 cu ft per hour for weld-puddle shielding and 5 to 10 cu ft per hour for backing is recommended.

In the following example, long, ductile crack-free welds were required in a cylinder made of thin metal. Microcracks appeared in the heat-affected zone when the cylinders were welded by the original method, but were eliminated when the backing bar was chromium plated.

Example 287. Elimination of Microcracks in the Heat-Affected Zone of an HS-25 Weldment (Fig. 18)

A bellows 25 in. in diameter and 30 in. long was formed from a cylinder 72 in. long made of 0.012-in.-thick HS-25 sheet. Two longitudinal welds were required in fabricating the cylinder (Fig. 18). The welds had to be ductile and crack-free so that the bellows convolutions could be formed without cracking and without adversely affecting the mechanical properties of the welds.

Originally, the cylinders were welded by the gas tungsten-arc process, without filler metal, using a welding positioner with cop-

per hold-down fingers and a copper backing bar. Transverse microcracks, up to about 0.10 in. long, through the work metal, appeared in the heat-affected zone. All attempts to eliminate the cracks, including increasing the welding speed, decreasing the clamping force, changing the shielding gas from argon to 25% argon – 75% helium and then to 95% argon – 5% hydrogen, and decreasing arc voltage, were unsuccessful.

When 0.030-in.-diam Hastelloy W filler-metal wire was used (instead of no filler metal), cracking was reduced to one or two repairable cracks in four or five welds, provided that the weld was less than 0.065 in. wide. However, at higher welding speeds, such as 60 in. per minute, it was difficult to feed the limited amount of wire needed to make the narrow weld. In addition, the occasional cracks that did occur were difficult to repair.

Because satisfactory welds had been made in tests on short lengths of HS-25 using no fixturing, methods of reducing tooling effect while maintaining alignment were considered, and a step taken was to plate the backing bar with 0.001 in. of hard chromium. Welds were made, with and without filler metal and with different welding currents, and all of the welds were crack-free. It was not known whether the cracks were initially caused by copper contamination of the weld metal or by heat dissipation due to the higher thermal conductivity of the copper, but the cracking was eliminated by chromium plating of the backing bar.

Forming of the convolutions was done with no cracking, indicating no significant adverse effect on the mechanical properties of the welds.

Welding conditions are given in the table that accompanies Fig. 18.

In the following example, gas tungsten-arc welding was used for repair of cracks in cobalt-base alloy castings.

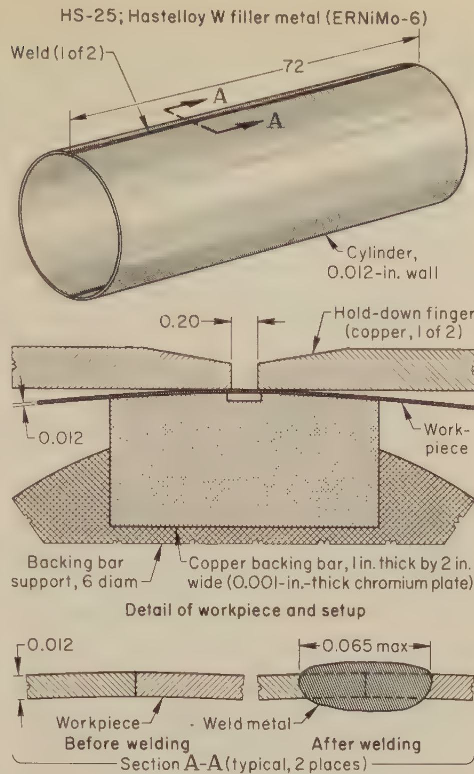
Example 288. Repair of Cracks in Cast HS-21 Gas-Turbine Nozzles (Fig. 19)

During gas-turbine overhaul, cracks were often detected in the vanes and shrouds of nozzles, most often appearing on the trailing edges of vanes. A section of a typical 9-in.-diam second-stage nozzle is shown in Fig. 19. Most of the defective nozzles were returned to service after repair by manual gas tungsten-arc welding. The repair procedure was as follows:

1. Remove heavy carbon coating and other surface contaminants by wire brushing and vapor degreasing.
2. Remove residual carbon by a proprietary chemical process, using strong alkaline cleaners and oxidizers, followed by light wet blasting of tough scaly areas or porous surfaces.
3. Heat treat castings at 2150 F for 15 min in a vacuum furnace, for final cleaning and solution treating.
4. Inspect castings by the fluorescent dye-penetrant method and mark cracks, using a special felt marker in which the ink is solvent soluble.
5. Grind out all cracks, using a small grinding wheel to cut slots (weld grooves) as shown in detail A of Fig. 19.
6. Fill the weld grooves by depositing HS-25 filler metal (AMS 5796) with low welding current and argon shielding.
7. Grind the weld surfaces to the proper contour.
8. Visually inspect ground surfaces.
9. Re-solution treat castings at 2150 F in a vacuum furnace.
10. Inspect welds, using fluorescent dye-penetrant method as before.
11. Wet blast all ground and blended areas for final finish.

The thickness of the vanes varied from 3⁄16 in. at the leading edge to 1⁄16 in. at the trailing edge. Hence, the weld beads had to be deposited with special care, using a foot-operated current control. Slotted areas were gradually built up by welding around the groove edges until the area was filled sufficiently to finish to size. It was not possible to weld the vanes from both sides. A small water-cooled torch with a 3⁄8 or 7⁄16-in.-diam cup and a 1⁄16-in.-diam gas lens was used for manipulating the 1⁄16-in.-diam tungsten electrode.

Parts repaired by this method proved acceptable after 25 hr of testing at various loads and a large number of cycles. In service, gas turbines with extensive casting weld repairs have exceeded 400 hr of service without failure.



Welding Conditions for Improved Method

Joint type	Butt
Weld type	Square groove
Welding process	Automatic gas tungsten-arc, automatic arc voltage with 0.25 sensing range
Power supply	300-amp transformer-rectifier
Electrode	0.045-in.-diam EWTh-2
Filler metal	0.030-in.-diam Hastelloy W
Torch	Water cooled
Shielding gas:	
At torch	Argon, 25% argon – 75% helium, or 95% argon – 5% hydrogen, at 15 to 25 cfh
Backing	Same gas as above, at 3 to 5 cfh
Welding position	Flat
Current	10 to 30 amp, dcsp
Voltage	11 to 19 v
Arc starting	High frequency
Travel speed	15 to 90 ipm
Wire feed	Automatically controlled
Fixture	Hold-down fingers and backing bar

Fig. 18. HS-25 cylinder that was welded without microcracking in the heat-affected zone when the backing bar was chromium plated (Example 287)

Gas Metal-Arc Welding. The wrought cobalt-base alloys can be welded automatically by gas metal-arc welding, using reverse-polarity direct current. The speed of welding, inherent to this process, can be an advantage in some applications, but care should be used to ensure that high heat input does not cause weld-metal cracking.

The shielding gas usually is argon, but argon with 1% oxygen is sometimes used. The electrode material selected should be compatible with the base metal and service requirements. Typical conditions for gas metal-arc welding are given in Table 9.

Shielded metal-arc welding can be used for joining cobalt-base alloys when service conditions permit and when it is not feasible to weld by a gas-shielded method. Reverse-polarity direct current results in the best mechanical properties. Welding should be done in the flat position, with rapid travel and as little weaving as possible.

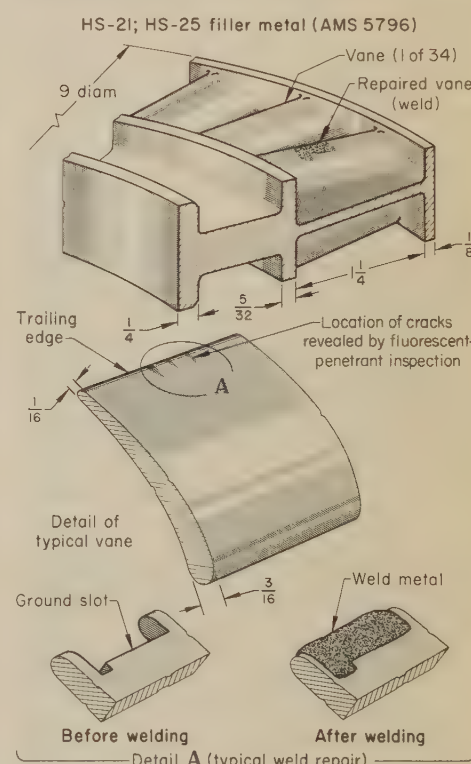
Table 9. Typical Conditions for Gas Metal-Arc Welding of Cobalt-Base Heat-Resisting Alloys

Base-metal thickness	1⁄8 to 3⁄8 in.
Filler-metal diameter	0.035 in.
Welding current	130 to 160 amp, dcrp
Voltage	22 to 25 v
Shielding gas	Argon + 1% oxygen; 40 cfh
Travel speed	30 ipm

Types of joint and proportions of weld grooves are the same as those used for nickel-base alloys. Cobalt-base alloys are welded in the solution-treated condition with electrodes that have a composition similar to that of the base metal being welded.

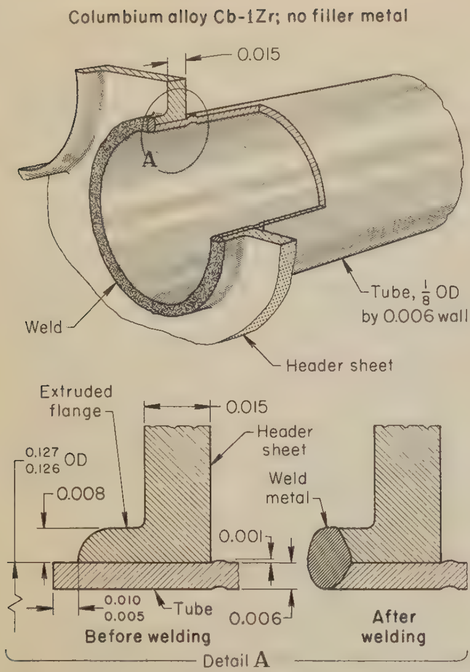
Refractory Metals

The refractory metals (columbium, tantalum, molybdenum and tungsten) can be welded by the gas tungsten-arc and electron beam processes. These metals must be welded in high-purity inert gas or in high vacuum to minimize contamination of the weld.



Weld type	Repair
Welding process	Manual gas tungsten-arc
Power supply	300-amp transformer-rectifier, with high-frequency current and time delay for gas and water
Electrode	1⁄16-in.-diam EWTh-2
Torch	Water cooled, with gas lens
Filler metal	1⁄16-in.-diam HS-25 (AMS 5796)
Shielding gas	Argon, at 10 to 15 cfh
Welding position	Flat
Current	12 to 70 amp, dcsp
Voltage	Not controlled
Arc starting	High frequency

Fig. 19. Section of a gas-turbine second-stage nozzle showing steps in the repair welding of a crack in the trailing edge of one of the vanes (Example 288)



Joint type	Edge flange
Torch	Light-duty, pencil type, air cooled(a)
Electrode	0.020-in.-diam EWP(b)
Filler metal	None
Shielding gas	Argon, in chamber
Current	20 to 25 amp, dcsp
Voltage	8 v
Welding speed	4.3 ipm
Welding time per tube	5.5 sec

(a) Mounted on a locating and guiding fixture. (b) Taper ground to a needle point.

Fig. 20. Joint between columbium alloy tube and header that was welded by the automatic gas tungsten-arc process (Example 289)

Preweld Cleaning. The refractory metals are susceptible to weld porosity, and sometimes to weld cracking, if not properly cleaned before being welded. Degreasing by wiping with acetone, followed by chemical cleaning, is necessary. After chemical cleaning, the work metal should be handled with clean cotton gloves and welded as soon as possible.

A procedure recommended for cleaning molybdenum alloys is as follows:

1. Immerse for 5 to 10 min in a warm (150 to 180 F) solution of (by weight) 10% sodium hydroxide and 5% potassium permanganate in distilled water.
2. Rinse in tap water, scrubbing off loose smut.
3. Immerse for 5 to 10 min in a room-temperature solution of (by volume) 15% concentrated sulfuric acid and 15% concentrated hydrochloric acid in distilled water, plus 6 to 10% (by weight) chromic acid.
4. Rinse in tap water and dry in air.

Glass or porcelain enameled containers are preferred for both solutions; stainless steel containers are unsatisfactory. If the work is not cleaned satisfactorily by the first cycle, the four steps can be repeated as necessary. Areas that resist treatment can be cleaned by pouring concentrated hydrochloric acid on them immediately after removal of the work metal from the smut-removing bath (step 3).

The same procedure can be used for cleaning tungsten, but reaction rates will be much slower and results not completely satisfactory.

Molybdenum and tungsten may also be cleaned by etching with a solution of (by volume) 90% concentrated nitric acid and 10% concentrated hydrofluoric acid. Reaction is vigorous, and the noxious gases emitted require forced-draft ventilation.

Tantalum alloys can be cleaned by immersing in a hot chromic dip or by chemically polishing in a solution of five volumes of 95% sulfuric acid, two volumes of 70% nitric acid, and two volumes of 48% hydrofluoric acid.

Columbium alloys may be cleaned with the following solutions:

1. 40% (by volume) HNO_3, 5% HF, remainder distilled water
2. 60% (by volume) HNO_3, 40% HF
3. 15% (by volume) H_2SO_4, 22% HF, remainder distilled water.

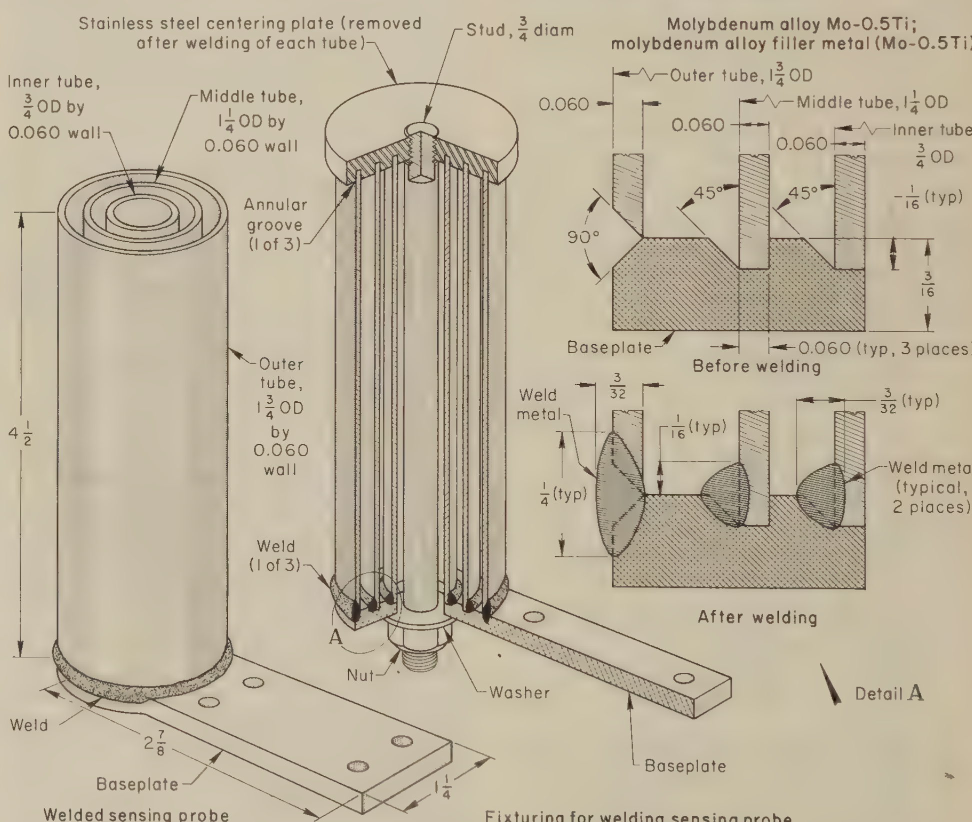
Columbium and Tantalum. Welds in pure columbium and tantalum are soft and ductile; they have very low ductile-to-brittle transition temperatures. During welding of columbium and tantalum alloys that contain carbon, rapid cooling from welding temperatures hardens the matrix of the weld zone and may give rise to brittleness at or near room temperature. The welded joint may age in service at elevated temperatures, with a loss in ductility. Postweld overaging treatments may be used to overcome aging embrittlement in service by increased precipitation of carbides or oxides, or both.

In the following example, the columbium alloy Cb-1Zr was edge welded by the gas tungsten-arc process.

Example 289. Gas Tungsten-Arc Welding of Edge Joints Between Columbium Alloy Cb-1Zr Tubes and Header (Fig. 20)

In the production of small heat exchangers for a high-temperature aerospace application, the ends of ⅛-in.-OD by 0.006-in.-wall tubes were edge-flange welded to a 0.015-in.-thick header. The tubes and header were made of columbium alloy Cb-1Zr, and were welded in the annealed condition. As shown in Fig. 20, each tube hole in the header had an extruded flange 0.008 in. thick that provided tube support as well as a low-restraint edge for welding. After the tubes and header were degreased and pickled, the tubes were inserted, with the ends protruding 0.005 to 0.010 in., and were expanded to the 0.126/0.127-in. inside diameter of the holes in the headers, and to provide each tube with a small embossed bead opposite the weld joint, which positioned the tube in the header (Fig. 20).

The assembly was gas tungsten-arc welded in a controlled-atmosphere chamber, under dry argon. Dry argon was used because of the embrittling effects of oxygen, nitrogen and hydrogen on the high-temperature properties of columbium alloys. Gas tungsten-arc welding was selected over electron beam welding mainly because the electron beam process would have entailed more expensive equipment, fixturing and tooling. Preliminary welds were made manually; the operation was later mechanized by mounting the torch on a locating and guiding fixture. Welding conditions are given in the table with Fig. 20.



Joint types	Outer tube, corner; middle and inner tubes, T
Weld types	Outer tube, single-V groove; middle and inner tubes, single-bevel groove
Electrode and filler metal	⅛-in.-diam EWTh-1 electrode; 0.060-in.-diam Mo-0.5Ti wire filler metal
Shielding gas	Reactor-grade helium, in a purge chamber
Current and voltage	250 amp, dcsp; 17 v(a)
Preheat(b)	1200 F (approx)

(a) From a 400-amp power supply. (b) Supplied by welding arc.

Fig. 21. Pressure and temperature-sensing probe made of molybdenum alloy Mo-0.5Ti and welded by the manual gas tungsten-arc process (Example 290)

Molybdenum and Tungsten. When molybdenum and tungsten are cooled from the molten state, or from temperatures near the melting point, interstitial impurities are rejected, usually to the grain boundaries, as oxides, nitrides and carbides. During welding, the interstitial compounds go back into solution, and during cooling are again rejected to the grain boundaries. Also, grain growth occurs, which decreases grain-boundary surface area. As a result, the weld metal and the metal in the heat-affected zone are weaker and less ductile than the base metal. Welds that are ductile at room temperature have been made in molybdenum but not in tungsten, because molybdenum is less sensitive to interstitial impurities than tungsten. The ductility of the weld is closely related both to the amount of interstitial impurities present and to the resulting grain size.

Welded joints are extremely notch sensitive; therefore, whenever possible, the weld metal should be finished smooth and faired gradually into the base metal. Notches at the root of the weld must be avoided.

Welds made in the molybdenum alloy Mo-0.5Ti have ductility comparable to welds in unalloyed molybdenum of similar interstitial content.

In the following example, the assembly was welded in a helium-filled chamber, with the use of a filler metal. The chamber was purged with the inert shielding gas, instead of by evacuating the chamber and then backfilling it with the inert gas.

Example 290. Joining Molybdenum Alloy Mo-0.5Ti Tubes to a Baseplate by Manual Gas Tungsten-Arc Welding (Fig. 21)

The tubes and baseplate that comprised the pressure and temperature-sensing probe shown in Fig. 21 were made of molybdenum alloy Mo-0.5Ti, and were joined by manual gas tungsten-arc welding. Welding was done in a purge chamber using reactor-grade helium as the shielding gas. The welding arc, manually traversed along the joints, provided preheating to about 1200 F.

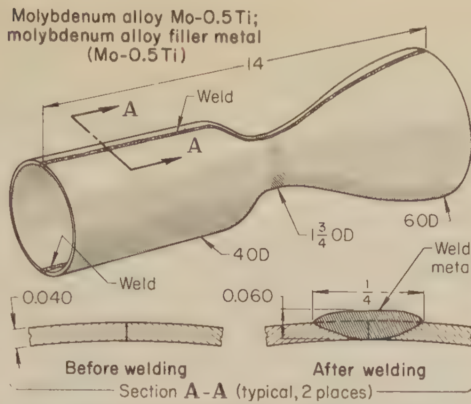
Before welding, all joint surfaces were machined, degreased with acetone, and chemically cleaned. The three tubes were located and held in place for welding by mating annular grooves machined in the Mo-0.5Ti alloy baseplate and a stainless steel centering plate; a nut and washer on a stud held the assembly together during welding (see Fig. 21).

The welding sequence for each joint, starting with the inner tube, was:

1 Displace air in the chamber by purging.
2 Test atmosphere purity using a test weld on a scrap piece of Mo-0.5Ti alloy (absence of discoloration indicated that atmosphere was satisfactory).
3 Preheat joint area to dull red color (about 1200 F) with welding arc.
4 Weld each joint in one pass, adding Mo-0.5Ti filler metal as needed.
5 After welding each joint, stress relieve the weldment in a dry hydrogen atmosphere (−75 F dew point) at 1900 ± 25 F for 1 hr.

After welding, the joints were inspected by the dye-penetrant method. Welding conditions are given with Fig. 21.

The two examples that follow describe the use of gas tungsten-arc welding in the production of nozzles from 0.040-in.-thick molybdenum alloy Mo-0.5Ti. In the first example, a filler metal was used but no fixture was needed. In the second example, no filler metal was used but fixtures and backing gas were needed.



Joint type	Longitudinal butt
Weld type	Square groove
Torch	Water cooled
Electrode	⅛-in.-diam EWTh-1
Filler metal	Mo-0.5Ti strips $\frac{1}{16}$ in. thick by ⅛ in. wide
Shielding gas	Argon, in a purge chamber
Current	150 amp, dcsp(a)
Voltage	17 v
Welding position	Flat
Fixture	None
Preheat(b)	1200 F (approx)

(a) From a 400-amp power supply. (b) Supplied by welding arc.

Fig. 22. Transpiration-cooled nozzle made of molybdenum alloy Mo-0.5Ti and joined by manual gas tungsten-arc welding (Example 291)

Example 291. Manual Gas Tungsten-Arc Welding of Mo-0.5Ti in a Purge Chamber, Using the Torch for Both Preheating and Welding (Fig. 22)

Figure 22 shows a transpiration-cooled nozzle that was produced as a weldment of two formed halves of 0.040-in.-thick molybdenum alloy Mo-0.5Ti. The two longitudinal joints were welded by the manual gas tungsten-arc process, in an atmosphere of argon in a purge chamber. Preheat of about 1200 F was provided by the welding arc, which was manually traversed.

Before welding, the joint edges were machined, and the two nozzle halves were chemically cleaned. No fixture was used during welding; instead, the two halves of the nozzle were held together by tungsten wires wrapped around the assembly and tightened by twisting the ends. During welding, Mo-0.5Ti filler metal was added as needed. Other welding conditions are given in the table that accompanies Fig. 22.

After the assemblies had been welded, the welds were dye-penetrant inspected; then the nozzle was stress relieved in dry hydrogen (−75 F dew point) for 1 hr.

Example 292. Automatic Gas Tungsten-Arc Welding of Mo-0.5Ti, Using Backing Gas and Copper Backing Fixtures (Fig. 23)

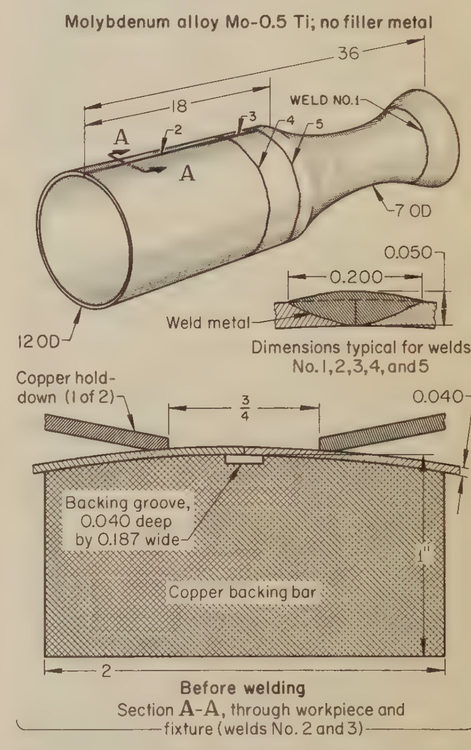
The ramjet combustion-chamber and exit-nozzle assembly shown in Fig. 23 was formed from molybdenum alloy Mo-0.5Ti sheet 0.040 in. thick, and was joined by automatic gas tungsten-arc welding. Reactor-grade helium at a flow rate of 20 cu ft per hour was used as leading and trailing shielding gas at the torch, and as backing gas for two joints. Argon backing gas at 3 cu ft per hour was used for three joints.

The components of the weldment were formed at 400 to 800 F from cross rolled stress-relieved sheet. Surface contamination and imperfections were removed by precision belt grinding 0.005 in. from each surface of the sheet before forming. The edges of the square-groove butt joints were machined and the components were degreased with acetone and then chemically cleaned.

Separate fixtures were used for each of the five welds shown in Fig. 23. The fixture for the circumferential throat weld (weld 1 in Fig. 23) was a copper backing ring with a groove for the argon backing gas. The fixture for the two longitudinal welds (welds 2 and 3 in Fig. 23) consisted of a copper backing bar, which also had a groove for the backing gas, and copper hold-down strips. A low-carbon steel fixture positioned the components for the circumferential welds in the combustion chamber (welds 4 and 5 in Fig. 23). Backing-gas protection for these welds was provided by the use of a counterbalanced floating shield matching the inside diameter of the chamber and extending over an arc of about 75°.

The metal at the joints for welds 1, 2 and 3 was preheated to 400 F by resistance heating elements embedded in the copper backing ring and bars. The metal at the joints for welds 4 and 5 was preheated to 325 F by quartz lamps. Postweld stress relieving at 1900 ± 25 F for 1 hr in dry hydrogen (−75 F dew point) was done after completion of each of the welds 1, 2, 3 and 5 (welds 4 and 5 were stress relieved by the same heat treatment).

Weld quality was checked by radiographic and dye-penetrant inspection methods. Welding conditions are given in the table with Fig. 23.



Joint type	Butt (longitudinal and circumferential)
Weld type	Square groove
Welding process	Automatic gas tungsten-arc
Torch	Mechanically held, water cooled
Electrode	$\frac{3}{32}$-in.-diam EWTh-1
Filler metal	None
Shielding gas	Helium and argon(a)
Current(b)	Welds 1, 2 and 3, 225 amp, dcsp; welds 4 and 5, 170 amp, dcsp
Voltage	16 to 16.5 v
Welding position	Flat
Preheat	Welds 1, 2 and 3, 400 F; welds 4 and 5, 325 F
Welding speed	40 ipm
Edge preparation	Machining, acetone degreasing, and chemical cleaning

(a) Reactor-grade helium, at 20 cu ft per hour, was used as leading and trailing shield at the torch, and as backing gas with a floating shield for welds No. 4 and 5. Welding-grade argon, at 3 cu ft per hour, was used as backing gas in grooves of backing ring for weld No. 1 and backing bar for welds No. 2 and 3. (b) From a 400-amp power supply.

Fig. 23. Ramjet combustion-chamber and exit-nozzle assembly made of molybdenum alloy Mo-0.5Ti, with five joints that were welded by the automatic gas tungsten-arc process (Example 292)

Arc Welding of Aluminum Alloys

*By the ASM Committee on Welding of Aluminum Alloys**

GAS METAL-ARC and gas tungsten-arc welding have almost entirely replaced other arc welding processes for aluminum alloys. These gas-shielded arc welding processes result in optimum weld quality and minimum distortion, and they require no flux. As a result, difficult-to-reach places and completely inaccessible interiors of welded assemblies are left free from flux residues that could be a potential source of corrosion. Furthermore, welding can be done in all positions, because there is no slag to be worked out of the weld by gravity or by puddling.

Visibility is good. The gas envelope around the arc is transparent, and the weld puddle is clean. A welder doing a hand welding job can make a neat, sound weld because he does not have to contend with smoke and fumes and can see what he is doing.

Base Metals

Most aluminum alloys can be joined by either gas metal-arc or gas tungsten-arc welding, and the weldabilities of aluminum alloys are essentially the same for both processes. The most common alloys are grouped by weldability rating in Table 1; nominal compositions are given in Table 2.

Wrought alloys most easily welded by gas-shielded arc processes are those of the non-heat-treatable 1*xxx*, 3*xxx* and 5*xxx* series; the alloys in the heat treatable 6*xxx* series are also easily welded. Alloys of the 4*xxx* series and of the high-strength, heat treatable 2*xxx* series can also be arc welded, but special techniques may be required and somewhat lower ductility may be obtained. Of the high-strength heat treatable 7*xxx* series, alloys 7075, 7079 and 7178 are weldable, but have brittle heat-affected zones, and therefore welding is usually not recommended, but alloys 7005 and 7039 were developed specifically for welding and have good weldability. Alloys 7005 and 7039 are of special interest for large structures in which the welds must be of high strength, because welds will age naturally to 70 to 90% of the strength of the heat treated base metal (depending on the chemical composition of the weld deposit) within 30 to 90 days after welding.

The heat of welding removes part or all of the effects of strain hardening; in consequence, the yield strength of the heat-affected zone of a weld in a non-heat-treatable alloy may not exceed that of the annealed alloy. The size of the low-strength zone will depend primarily on the speed of welding and the amount of strain hardening. On the whole, weldments exhibit good joint efficiency and ductility.

Table 1. Weldability of Aluminum Alloys by the Gas Metal-Arc and Gas Tungsten-Arc Processes (a)

Readily Weldable

Wrought alloys(b):
Pure aluminum, EC, 1060, 1100
2219
3003, 3004
5005, 5050, 5052, 5083, 5086, 5154, 5254, 5454, 5456, 5652
6061, 6063, 6101, 6151
7005, 7039
Casting alloy: 43

Weldable in Most Applications
(May require special techniques for some applications)

Wrought alloys: 2014, 4032
Casting alloys:
13, 108, A108
214, A214, B214, F214
319, 333, 355, C355, 356
A612, C612, D612

Limited Weldability
(Require special techniques)

Wrought alloy: 2024
Casting alloys: 138, 195, B195

Welding Not Recommended

Wrought alloys: 7075, 7079, 7178
Casting alloys: 122, 142, 220

(a) Wrought alloys are listed here by Aluminum Association designations; casting alloys, by industry designations. See Table 2 for nominal compositions of all alloys listed, and for Aluminum Association designations of casting alloys. (b) See Table 14 on page 877 in Volume 1 of this Handbook for strength and ductility of gas metal-arc welded joints in many of these alloys and combinations of these alloys, using various filler metals.

When a heat treated alloy (T4 or T6 condition) is arc welded, its strength in the as-welded condition is slightly less than that of the unwelded alloy in the T4 condition. This decrease in strength is attributed to the comparative weakness of the heat-affected zone. The zone normally consists of an area of solution-annealed material adjacent to the weld, an area where partial annealing has occurred, and an overaged area. Because of the high strength of the base metal and the low strength of the heat-affected zone, weldments of alloys in the T6 condition have a low as-welded joint efficiency and often a lack of ductility. Solution heat treatment and aging after welding may restore much of the strength, but little improvement in ductility occurs. After postweld aging alone, the strength may be no higher, and the ductility can be lower, than those of some non-heat-treatable alloys. To obtain optimum properties of weldments, it may be preferable to weld in the annealed condition, and to solution heat treat and age afterward.

There is little difference between the strengths of welded and unwelded heat treatable and non-heat-treatable alloys in the annealed condition.

Casting Alloys. Most casting alloys can be gas-shielded arc welded if they are given the correct edge preparation. Aluminum sand and permanent mold castings are welded to repair foundry defects, to repair items broken in service, or to join cast fittings to wrought members. Formerly, die-cast fittings were seldom used where welded construction was required, because they often contained porosity, but recent advances in casting technique, such as vacuum die casting, have resulted in improved quality; die castings are now satisfactorily welded for some applications, such as irrigation tubing.

Filler Metals

Classifications and compositions of filler metals for gas metal-arc and gas tungsten-arc welding of aluminum al-

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Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees. References to examples that appear elsewhere in this volume are given on page 336.

Table 2. Nominal Compositions of Aluminum Alloys

Alloy	Composition, %
Wrought Aluminum Alloys(a)	
1060	99.60 Al (min)
EC	99.45 Al (min)
1100	0.12 Cu, 99.00 Al (min)
2014	0.8 Si, 4.4 Cu, 0.8 Mn, 0.5 Mg
2024	4.4 Cu, 0.6 Mn, 1.5 Mg
2219	6.3 Cu, 0.3 Mn, 0.18 Zr, 0.1 V
3003	0.12 Cu, 1.2 Mn
3004	1.2 Mn, 1.0 Mg
4032	12.2 Si, 0.9 Cu, 1.1 Mg, 0.9 Ni
5005	0.8 Mg
5050	1.4 Mg
5052	2.5 Mg, 0.25 Cr
5083	0.6 Mn, 4.45 Mg, 0.15 Cr
5086	0.45 Mn, 4.0 Mg, 0.15 Cr
5154	3.5 Mg, 0.25 Cr
5254	2.5 Mg
5454	0.8 Mn, 2.7 Mg, 0.12 Cr
5456	0.8 Mn, 5.1 Mg, 0.12 Cr
5652	2.5 Mg, 0.25 Cr
6061	0.6 Si, 0.27 Cu, 1.0 Mg, 0.2 Cr
6063	0.4 Si, 0.7 Mg
6101	0.5 Si, 0.6 Mg
6151	0.9 Si, 0.6 Mg, 0.25 Cr
7005	0.45 Mn, 1.4 Mg, 0.13 Cr, 4.5 Zn
7039	0.27 Mn, 2.8 Mg, 0.2 Cr, 4.0 Zn
7075	1.6 Cu, 2.5 Mg, 0.3 Cr, 5.6 Zn
7079	0.6 Cu, 0.2 Mn, 3.3 Mg, 0.2 Cr, 4.3 Zn
7178	2.0 Cu, 2.7 Mg, 0.3 Cr, 6.8 Zn
Aluminum Casting Alloys(b)	
13 (413.0)	12.0 Si
43 (443.0)	5.0 Si
108 (208.0)	4.0 Cu, 3.0 Si
A108 (308.0)	4.5 Cu, 5.5 Si
122 (222.0)	10.0 Cu, 0.2 Mg
138 (238.0)	10.0 Cu, 4.0 Si, 0.3 Mg
142 (242.0)	4.0 Cu, 1.5 Mg, 2.0 Ni
195 (295.0)	4.5 Cu, 0.8 Si
B195 (B295.0)	4.5 Cu, 2.5 Si
214 (514.0)	3.8 Mg
A214 (A514.0)	3.8 Mg, 1.8 Zn
B214 (B514.0)	1.8 Si, 3.8 Mg
F214 (F514.0)	0.5 Si, 3.8 Mg
220 (520.0)	10.0 Mg
319 (319.0)	3.5 Cu, 6.0 Si
333 (333.0)	3.8 Cu, 9.0 Si
355 (355.0)	1.3 Cu, 5.0 Si, 0.5 Mg
C355 (C355.0)	1.3 Cu, 5.0 Si, 0.5 Mg, 0.2 Fe max
356 (356.0)	7.0 Si, 0.3 Mg
A612 (A712.0)	0.5 Cu, 0.7 Mg, 6.5 Zn
C612 (C712.0)	0.5 Cu, 0.35 Mg, 6.5 Zn, 1.0 Fe
D612 (D712.0)	0.6 Mg, 5.3 Zn, 0.5 Cr

(a) Wrought alloys are identified by Aluminum Association designations. (b) Casting alloys are identified first by industry designations, and then parenthetically by Aluminum Association designations.

loys are given in Table 3. In addition, filler metals having the same composition as the base-metal alloy are often used for repairing casting defects.

Selection of Filler Metal. Common criteria to be considered in selecting a filler metal are ease of welding, strength, ductility, resistance to corrosion of the filler metal – base metal combination, color match with the base metal after anodizing, and service at elevated temperature. The filler metals listed in Table 3 have been developed to satisfy these requirements. A guide for selection of the filler metal that gives the optimum combination of these criteria for general welding of a selection of alloy combinations is shown in Table 4. Tables 5 and 6 rate filler metals for specific welding criteria — namely, ease of welding, as-welded joint strength and ductility, corrosion and heat resistance, and color match after anodizing.

Joint Design and Edge Preparation

In general, joint design for aluminum alloys is similar to that for steel (see the illustrations in the article on Recommended Proportions of Grooves for Arc Welding, beginning on page 148 in this volume). The fact that the fluidity of aluminum during welding is higher than that of steel makes for some differences: for example, in thin sheet, the root opening is smaller. Recommended butt-joint designs for gas-shielded arc welding are shown in Fig. 1. When using straight-polarity direct-current gas tungsten-arc welding, the root face can be thicker and the grooves narrower. Some butt-joint designs used for gas metal-arc welding are shown in Fig. 6 and Table 9.

Lap joints are used more often for aluminum alloys than for most other metals. The efficiency of lap joints is 60 to 80%, depending on the alloy and temper. Lap joints offer the advantages of no edge preparation being required and ease of fit-up, but have the disadvantage that inspection of the weld is difficult. Preferred types of lap joints are shown in Fig. 2.

T-joints are also widely used. Beveling is seldom required, but it is used on thick material to reduce welding costs and to minimize distortion.

Welding a lap joint or a T-joint on one side only is not recommended. It is better to use a small continuous fillet weld on each side of the joint.

Edge Preparation and Assembly. Material up to about ⅜ in. thick can be sheared to a reasonably square edge that can be cleaned readily. Shear blades should be kept free of oil and foreign material; the aluminum should be degreased before shearing if there is excessive lubricant on the surface.

Band sawing, using a stick-wax lubricant, can be employed for edge preparation of metal several inches thick. After sawing, all lubricant should be removed from the sawed surface.

Usually, no lubricant is used when machining joint edges. When a lubricant must be used, sharp cutting tools of correct design should be employed. Dull or improperly designed tools result in prepared edges that can trap lubricant, which can cause weld porosity.

The extra time needed to ensure a close fit is often less than the extra time required in welding an improperly prepared assembly. Better fit and uniformity of the joint are required for automatic and out-of-position welding than for semiautomatic and flat-position welding. Automatic gas tungsten-arc welding of aluminum less than ⅛ in. thick requires that joint fit-up should be held within 0.003 to 0.010 in., depending on metal thickness. A very close fit of the edges is also essential when gas tungsten-arc welding without the addition of filler metal.

Aluminum alloy extrusions are sometimes produced with edge designs that facilitate welding. Besides edge preparation, the design may include (*a*) self-aligning mechanical fitting (see Example 294); (*b*) integral weld backing (see Example 311 and section F-F in Fig. 36); or (*c*) an increase in section thickness at the joint area to make welding easier, or (as in Example 319) to compensate for the lower unit strength of the weld area than of the base metal — which is especially valuable in butt welds in heat treatable alloys used in structures too large for most furnaces used for postweld heat treating.

Preweld Cleaning

Preweld cleaning of aluminum is essential for optimum weld quality. Precleaning requirements are especially stringent prior to straight-polarity direct-current gas tungsten-arc welding, because under such conditions the arc exerts no cleaning action. However, the highest-quality welds are not always needed. Where service requirements permit, many aluminum parts are welded with no preweld cleaning at all.

Surface contaminants that should be removed from the base metal include dirt, metal particles, oil and grease, paint, moisture, and heavy oxide coatings. Another source of contamination is oxide film on the filler metal. Base metals such as 1100 and 3003 have a relatively thin oxide coating as-fabricated, and the 5*xxx* and 6*xxx* series al-

Table 3. Compositions of Consumable Electrodes and Filler Metals for Gas Metal-Arc and Gas Tungsten-Arc Welding of Aluminum Alloys (AWS A5.10-69) (a)

AWS classification	Composition, %
ER1100	1.0 Si+Fe, 0.05-0.20 Cu, 0.05 Mn, 0.10 Zn, 99.00 Al (min)
ER1260	0.40 Si+Fe, 0.04 Cu, 0.01 Mn, 99.60 Al (min)
ER2319	0.20 Si, 0.30 Fe, 5.8-6.8 Cu, 0.20-0.40 Mn, 0.02 Mg, 0.10 Zn, 0.10-0.20 Ti
ER4043	4.5-6.0 Si, 0.8 Fe, 0.30 Cu, 0.05 Mn, 0.05 Mg, 0.10 Zn, 0.20 Ti
ER4047	11.0-13.0 Si, 0.8 Fe, 0.30 Cu, 0.15 Mn, 0.10 Mg, 0.20 Zn
ER4145	9.3-10.7 Si, 0.8 Fe, 3.3-4.7 Cu, 0.15 Mn, 0.15 Mg, 0.15 Cr, 0.20 Zn
ER5039	0.10 Si, 0.40 Fe, 0.03 Cu, 0.30-0.50 Mn, 3.3-4.3 Mg, 0.10-0.20 Cr, 2.4-3.2 Zn, 0.10 Ti
ER5183	0.40 Si, 0.40 Fe, 0.10 Cu, 0.50-1.0 Mn, 4.3-5.2 Mg, 0.05-0.25 Cr, 0.25 Zn, 0.15 Ti
ER5356	0.50 Si+Fe, 0.10 Cu, 0.05-0.20 Mn, 4.5-5.5 Mg, 0.05-0.20 Cr, 0.10 Zn, 0.06-0.20 Ti
ER5554	0.40 Si+Fe, 0.10 Cu, 0.50-1.0 Mn, 2.4-3.0 Mg, 0.05-0.20 Cr, 0.25 Zn, 0.05-0.20 Ti
ER5556	0.40 Si+Fe, 0.10 Cu, 0.50-1.0 Mn, 4.7-5.5 Mg, 0.05-0.20 Cr, 0.25 Zn, 0.05-0.20 Ti
ER5654(b)	0.45 Si+Fe, 0.05 Cu, 0.01 Mn, 3.1-3.9 Mg, 0.15-0.35 Cr, 0.20 Zn, 0.05-0.15 Ti
R-C4A(c)	1.5 Si, 1.0 Fe, 4.0-5.0 Cu, 0.35 Mn, 0.03 Mg, 0.35 Zn, 0.25 Ti
R-CN42A(c)	0.7 Si, 1.0 Fe, 3.5-4.5 Cu, 0.35 Mn, 1.2-1.8 Mg, 0.25 Cr, 1.7-2.3 Ni, 0.35 Zn, 0.25 Ti
R-SC51A(c)	4.5-5.5 Si, 0.8 Fe(d), 1.0-1.5 Cu, 0.50 Mn(d), 0.40-0.60 Mg, 0.25 Cr, 0.35 Zn, 0.25 Ti
R-SG70A(c)	6.5-7.5 Si, 0.6 Fe, 0.25 Cu, 0.35 Mn, 0.20-0.40 Mg, 0.35 Zn, 0.25 Ti

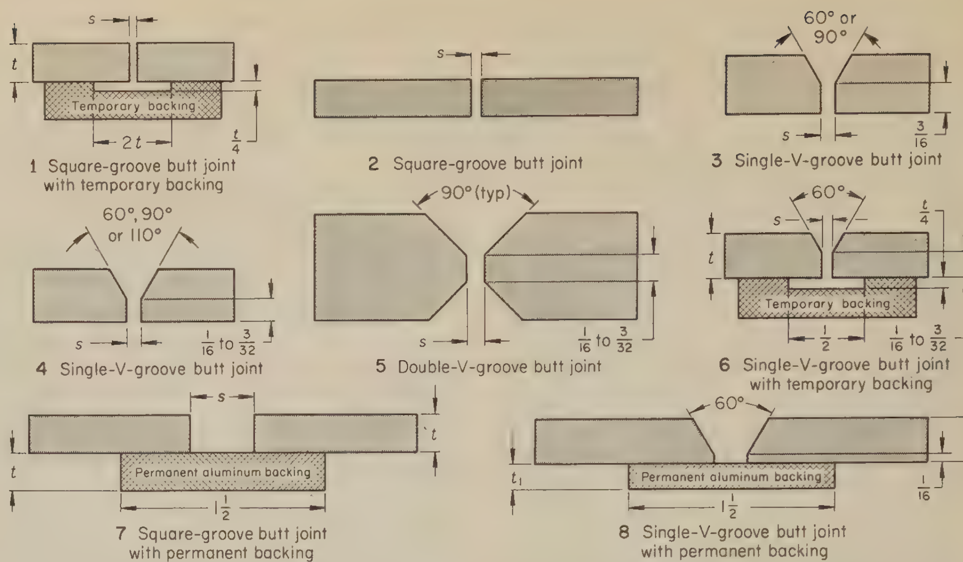
(a) Single values are maximums, except for aluminum content of ER1100 and ER1260. (b) ER5654 replaces ER5154, ER5254 and ER5652. (c) For repair of castings. (d) If iron exceeds 0.45%, manganese should be equal to one-half the iron content.

Table 4. Filler Metals Suitable for General-Purpose Gas-Shielded Arc Welding of Various Combinations of Aluminum Alloy Base Metals

Base metals to be welded (in column below, and in column heads at right)	319, 333, 355, C355	13, 43, 356	214, A214, B214, F214	7005, 7039, A612, C612, D612	6061, 6063, 6101, 6151	5456	5454	5154, 5254*a*	5086	5083	5052, 5652*a*	5005, 5050	3004, alclad 3004	2219	2014, 2024	1100, 3003, alclad 3003	1060, EC
1060, EC	4145*b,c*	4043*c,d*	4043*c,e*	4043*c*	4043*c*	5356*b*	4043*c,e*	4043*c,e*	5356*b*	5356*b*	4043*c*	1100*b*	4043	4145	4145	1100*b*	1260*b,j*
1100, 3003, alclad 3003	4145*b,c*	4043*c,d*	4043*c,e*	4043*c*	4043*c*	5356*b*	4043*c,e*	4043*c,e*	5356*b*	5356*b*	4043*c,e*	4043*e*	4043*e*	4145	4145	1100*b*	
2014, 2024	4145*g*	4145	...	...	4145	...	...	...	...	...	...	...	...	4145*g*	4145*g*		
2219	4145*b,c,g*	4145*b,c*	4043*c*	4043*c*	4043*c,d*	4043	4043*c*	4043*c*	4043	4043	4043*c*	4043	4043	2319*b,c,d*			
3004, alclad 3004	4043*c*	4043*c*	5654*h*	5356*e*	4043*h*	5356*e*	5654*h*	5654*h*	5356*e*	5356*e*	4043*c,e*	4043*e*	4043*e*				
5005, 5050	4043*c*	4043*c*	5654*h*	5356*e*	4043*h*	5356*e*	5654*h*	5654*h*	5356*e*	5356*e*	4043*c,e*	4043*e,j*					
5052, 5652*a*	4043*c*	4043*c,h*	5654*h*	5356*e,k*	5356*b,h*	5356*h*	5654*h*	5654*a,h*	5356*e*	5356*e*	5654*a,b,h*						
5083	...	5356*b,c,e*	5356*e*	5183*e,k*	5356*e*	5183*e*	5356*e*	5356*e*	5356*e*	5183*e*							
5086	...	5356*b,c,e*	5356*e*	5356*e,k*	5356*e*	5356*e*	5356*h*	5356*h*	5356*e*								
5154, 5254*a*	...	4043*c,h*	5654*h*	5356*h,k*	5356*b,h*	5356*h*	5654*h*	5654*a,h*									
5454	4043*c*	4043*c,h*	5654*h*	5356*h,k*	5356*b,h*	5356*h*	5554*b,e*										
5456	...	5356*b,c,e*	5356*e*	5556*e,k*	5356*e*	5556*e*											
6061, 6063, 6101, 6151	4145*b,c*	4043*c,h*	5356*b,h*	5356*b,c,h,k*	4043*c,h*												
7005, 7039, A612, C612, D612	4043*c*	4043*c,h,k*	5356*h,k*	5039*e*													
214, A214, B214, F214	...	4043*c,h*	5654*h,j*														
13, 43, 356	4145*b,c*	4043*c,j*															
319, 333, 355, C355	4145*b,c,j*																

NOTE: All filler metals shown here are covered by AWS specification A5.10-69, prefixed by the letters "ER". Throughout this table, the prefix has been omitted, to conserve space. Filler metals 5356, 5556 and 5654 are not suitable for sustained service at temperatures higher than 150 F. Other service conditions, such as immersion in fresh or salt water or exposure to specific chemicals, may also limit the choice of filler metal. Where no filler metal is listed, the base-metal combination is not recommended for welding.

(*a*) Base metals 5254 and 5652 are used for hydrogen peroxide service. Filler metal 5654 is used for welding both alloys for service at temperatures of 150 F and below. (*b*) 4043 may be used for some jobs. (*c*) 4047 may be used for some jobs. (*d*) 4145 may be used for some jobs. (*e*) 5183, 5356 or 5556 may be used. (*f*) 1100 may be used for some jobs. (*g*) 2319 may be used for some jobs. (*h*) 5183, 5356, 5554, 5556 and 5654 may be used. In some cases they provide improved color match after anodizing treatment, highest weld ductility, and higher weld strength. Filler metal 5554 is suitable for service at elevated temperature. (*j*) Filler metal of the same composition as the base metal is sometimes used. (*k*) 5039 may be used for some jobs.



Metal thickness, *t*, in.	Semiautomatic gas metal-arc welding: Welding position(a)	Joint design(b)	Root opening, *s*, in.	Manual gas tungsten-arc welding: Welding position(a)	Joint design	Root opening, *s*, in.
1/16	F	1, 7	0–3/32	F,H,V,O	2	0
3/32	F	1	0	F,H,V	2	0
	F,H,V,O	7	1/8	O	2	0
1/8	F,H,V	1	0–3/32	F	2	0
	F,H,V,O	7	3/16	H,V,O	2	0
3/16	F,H,V	2	0	F	4-60°	0–1/8
	F,H,V,O	6	0–1/16	H	4-90°	0–3/32
	F,V	8	3/32–3/16	V	4-60°	0–3/32
	H,O	8	3/16	O	4-110°	0–3/32
1/4	F	2	0	F	4-60°	0–1/8
	F,H,V,O	6	0–3/32	H	4-90°	0–3/32
	F,V	8	1/8–1/4	V	4-60°	0–3/32
	H,O	8	1/4	O	4-110°	0–3/32
3/8	F	3-90°	0–3/32	F	4-60°	0–1/8
	F	6	0–3/32	F	5	0–3/32
	H,V,O	6	0–3/32	V	4-60°	0–3/32
	F,V	8	1/4–3/8	H,V,O	5	0–3/32
	H	8	3/8	H	4-90°	0–3/32
	O	8	3/8	O	4-110°	0–3/32
3/4	F	3-60°	0–3/32	...	...	...
	F	8	0–1/8	...	...	...
	H,V,O	8	0–1/16	...	...	...
	F,H,V,O	8	0–1/16	...	...	...

(a) F = flat; H = horizontal; V = vertical; O = overhead. (b) For design 8, $t_1 = t$ for t less than 3/8 in., and t_1 = 3/8 in. for t greater than 3/8 in.

Fig. 1. Recommended butt-joint designs for the gas metal-arc welding (dcrp) and gas tungsten-arc welding (ac) of aluminum alloys. Joints 2, 3, 4, 5 and 6 should be back gouged to solid weld metal before applying a pass on the root side.

loys generally have a thick, dark oxide coating. The thicker the oxide, the greater its adverse effect on weld-metal flow and solidification and the greater the risk of porosity. Any foreign material that remains on the surfaces to be welded is a potential source of unsound welds. For best results, all cleaning and oxide removal should be done immediately before welding.

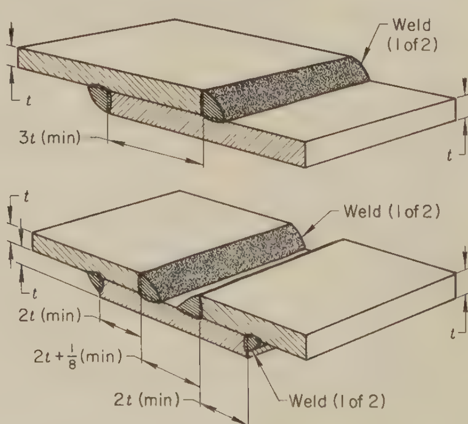


Fig. 2. Preferred types of lap joints for arc welding of aluminum alloys

First, the work-metal surface should be cleaned of contaminants. The following manual cleaning methods can be used for small production runs. Dirt can be removed easily by washing and scrubbing with a detergent solution; an effective drying procedure is necessary to ensure that no moisture is present on the surfaces to be welded. Removal of grease and oil can be accomplished by swabbing with solvent-soaked cloths. Suitable solvents include

Footnotes for Table 5

(a) Rating applies particularly to fillet welds. All filler alloys rated will develop presently specified minimum strengths in butt welds. (b) Rating based on continuous or alternate immersion in fresh or salt water. (c) Rating based on free-bend elongation of weld.

(d) Filler alloy 5183 has the same ratings as 5556, except that welds made with 5183 are slightly more ductile and, in cases where the filler metal controls the weld strength, slightly less strong than welds made with 5556. Because of its lower strength, 5183 filler metal is not recommended for welding 5456.

(e) Filler-metal alloys 5356 and 5556 are not recommended for corrosion resistance in welding alloy 1100, 3003 or 3004 to bare alloy 3003 or 3004, but are rated B for corrosion resistance in welding alloy 1100 or 3003 to alclad 3003 or 3004, and rated C for corrosion resistance in welding alloy 3004 to alclad 3004. (f) Ratings do not apply when heat treated after welding.

Table 5. Filler Metals Commonly Used in Arc Welding Combinations of Aluminum Alloys
(Ratings are relative, in decreasing order of merit, and apply only within a given block. Combinations having no rating are not recommended.)

Alloys to be welded	Ease of welding						Strength of welded joint (as-welded)(a)						Corrosion resistance(b)						Service at sustained temp above 150 F						Color match after anodizing						Ductility(c)					
Filler alloy (d)	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556
To weld alloy 1100 to:																																				
1100	B	A	–	C	–	C	B	A	–	A	–	A	A	A	–	–	–	–	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
3003, alclad 3003	A	A	–	B	–	B	B	A	–	A	–	A	A	A	–	(e)	–	(e)	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
3004, alclad 3004	C	A	–	B	–	B	B	A	–	A	–	A	A	A	–	(e)	–	(e)	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
5005, 5050	B	A	–	B	–	B	B	A	–	A	–	A	A	A	–	–	–	–	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
5052, 5154, 5454	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5083, 5086, 5456	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6063(f), 6101(f)	–	A	–	B	–	B	–	A	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(f)	–	A	–	B	–	B	–	A	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alloy 3003 to:																																				
3003, alclad 3003	A	A	–	B	–	B	C	B	–	A	–	A	A	A	–	(e)	–	(e)	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
3004, alclad 3004	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	(e)	–	(e)	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5005, 5050	B	A	–	B	–	B	C	B	–	A	–	A	A	A	–	–	–	–	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
5052	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	B	A	A	A	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	B	–	A	A	A	–	C	–	B	A	B	–	A	–	–	A	–	–	–	–	A	A	A	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A		B	–	A	–	A	–	B	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6063(f), 6101(f)	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(e)	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alclad 3003 to:																																				
Alclad 3003	A	A	–	B	–	B	C	B	–	A	–	A	A	A	–	B	–	B	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
3004, alclad 3004	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5005, 5050	B	A	–	B	–	B	C	B	–	A	–	A	A	A	–	B	–	B	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
5052	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	B	A	A	A	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	B	–	A	A	A	–	C	–	B	A	B	–	A	–	–	A	–	–	–	–	A	A	A	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A	–	B	–	A	–	A	–	B	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6063(f), 6101(f)	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(f)	–	A	–	B	–	B		B	–	A	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alloy 3004 to:																																				
3004, alclad 3004	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B	(e)	B	(e)	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
5005, 5050	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5052	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	D	C	B	C	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	D	–	B	C	A	–	C	–	B	A	B	–	A	–	–	A	–	–	–	–	A	A	A	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A	–	C	–	B	–	A	–	B	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6063(f), 6101(f)	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(f)	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alclad 3004 to:																																				
Alclad 3004	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B	C	B	C	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
5005, 5050	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5052	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	D	C	B	C	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	D	–	B	C	A	–	C	–	B	A	B	–	A	–	–	A	–	–	–	–	A	A	A	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A	–	C	–	B	–	A	–	B	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6063(f), 6101(f)	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(f)	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	B	–	B	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alloy 5005 or 5050 to:																																				
5005, 5050	C	A	–	B	–	B	–	B	–	A	–	A	A	A	–	–	–	–	A	A	–	–	–	–	A	–	–	B	–	B	A	D	–	B	–	C
5052	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	B	A	A	A	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	B	–	A	A	A	–	C	–	B	A	B	–	A	–	–	A	–	–	–	–	A	A	A	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A	–	B	–	A	–	A	–	B	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6063(f), 6101(f)	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
6061(f)	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	A	–	–	–	–	–	–	–	A	–	A	–	C	–	A	–	B
To weld alloy 5052 to:																																				
5052	–	A	B	A	C	A	–	D	C	B	C	A	–	C	B	–	B	–	–	A	–	–	B	–	–	–	A	A	B	B	–	C	A	A	A	B
5154	–	A	B	A	C	A	–	D	C	B	C	A	–	C	A	B	A	B	–	–	–	–	–	–	–	–	A	A	B	B	–	C	A	A	A	B
5454	–	A	B	A	C	A	–	D	C	B	C	A	–	C	B	B	A	B	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
5083, 5086, 5456	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	–	–	A	–	B
6063(f), 6101(f)	–	A	C	B	C	B	–	B	A	A	A	A	–	A	B		B	–	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B		B	–	–	A	–	–	A		–	–	A	A	B	B	–	C	A	A	A	B
To weld alloy 5083 or 5456 to:																																				
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	–	A	A	A	B
5454	–	–	–	A	B	A	–	–	–	B	C	A	–	–	–	B	A	B	–	–	–	–	–	–	–	–	–	A	A	A	–	–	–	A	A	B
5083, 5086, 5456	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	–	–	A	–	B
6063(f), 6101(f)	–	A	B	A	B	A	–	B	A	A	A	A	–	A	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	B	A	B	A	–	D	C	B	C	A	–	A	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
To weld alloy 5086 to:																																				
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	–	A	A	A	B
5454	–	–	–	A	B	A	–	–	–	B	C	A	–	–	–	B	A	B	–	–	–	–	–	–	–	–	–	A	A	A	–	–	–	A	A	B
5086	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	–	–	–	–	–	–	A	–	A	–	–	–	A	–	B
6063(f), 6101(f)	–	A	B	A	B	A	–	B	A	A	A	A	–	A	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	B	A	B	A	–	D	C	B	C	A	–	A	A	A	A	A	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
To weld alloy 5154 to:																																				
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	–	A	–	–	–	–	–	–	–	–	–	A	A	B	B	–	–	A	A	A	B
5454	–	–	B	B	B	A	–	–	C	B	C	A	–	–	A	B	A	B	–	–	–	–	–	–	–	–	B	A	A	A	–	–	A	A	A	B
6063(f), 6101(f)	–	A	C	B	C	B	–	B	A	A	A	A	–	A	B	–	B	–	–	–	–	–	–	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B	–	B	–	–	–	–	–	–	–	–	–	A	A	B	B	–	C	A	A	A	B
To weld alloy 5454 to:																																				
5454	–	–	B	A	B	A	–	–	C	B	C	A	–	–	B	B	A	B	–	–	–	–	A	–	–	–	B	A	A	A	–	–	A	A	A	B
6063(f), 6101(f)	–	A	C	B	C	B	–	B	A	A	A	A	–	B	B	–	A	–	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	C	B	C	B	–	D	C	B	C	A	–	B	B	–	A	–	–	A	–	–	A	–	–	–	B	A	A	A	–	C	A	A	A	B
To weld alloy 6061 to:																																				
6063(f), 6101(f)	–	A	C	B	C	B	–	B	A	A	A	A	–	A	B	C	B	C	–	A	–	–	B	–	–	–	B	A	A	A	–	C	A	A	A	B
6061(f)	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B	C	B	C	–	A	–	–	B	–	–	–	B	A	B	B	–	C	A	A	A	B
To weld alloy 6063 or 6101 to:																																				
6063(f), 6101(f)	–	A	C	B	C	B	–	B	A	A	A	A	–	A	B	C	B	C	–	A	–	–	B	–	–	–	B	A	A	A	–	C	A	A	A	B

For footnotes, see facing page.

butyl alcohol, naphtha, acetone, carbon tetrachloride, and trichlorethylene. Butyl alcohol, naphtha and acetone must be used with care, because they are flammable; carbon tetrachloride and trichlorethylene should be used only with effective ventilation, and well away from the welding area, because they decompose and produce toxic fumes when contacted by the arc.

Next, heavy oxide layers should be mechanically removed with a wire brush, steel wool, mill file, portable milling tool, or a scraper. The use of abrasive paper or grinding disks alone is not recommended, because particles of the abrasive may become embedded in the aluminum and, unless subsequently removed, can cause inclusions in the weld. Wire brushes should have sharp bristles and should be kept free of oil and other foreign material; bristles preferably should be 0.012 to 0.016 in. in diameter and of stainless steel, to minimize iron oxide pickup.

Motor-driven wire brushes should be used carefully. If excessive pressure is applied, a burnishing action in which the oxide is rolled into the freshly exposed surface will result, and the weld may be of poorer quality than one made without wire brushing. However, enough pressure has to be used to cause the sharp bristles to break the oxide from the surface of the aluminum alloy.

Chemical removal of oxides can be accomplished by immersion in solutions of the butyl alcohol – phosphoric acid type. After the chemical treatment, the parts should be washed thoroughly with water and dried with hot air.

For thick and persistent oxide coatings, immersion in a 5% sodium hydroxide solution at 150 F for about 30 sec is recommended. This treatment leaves a dark smut on the surface. To remove the smut, the treatment should be followed by a cold water rinse, immersion in a solution containing equal parts of commercial nitric acid and water at room temperature, a final water rinse (preferably hot) and hot air drying. Heavy-etching caustic solutions are not recommended, because the rough surface that they produce is likely to collect hydrocarbons and foreign material.

It is preferable that degreasing and chemical cleaning be done before the parts are assembled for welding. Cleaning after assembly can result in retention of foreign material and solutions between abutting edges and lapped areas of the joint, and porosity and dross entrapment in the weld are likely to result.

Freshly machined and freshly filed surfaces are the cleanest and are often specified when the ultimate in weld quality is demanded.

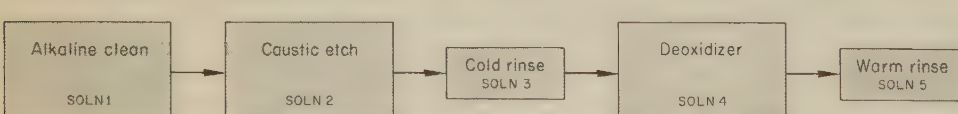
Occasionally, special precleaning methods are used to solve a specific problem, as in the following example:

Table 6. Guide to Selection of Filler-Metal Alloys for Arc Welding Various Combinations of Heat Treatable Aluminum Alloys

(Ratings are relative, in decreasing order of merit, and apply to a given base-metal combination and postweld condition. The use of base metals as filler metals, or of combinations indicated here by dashes as having no ratings, is not recommended.)

Alloys to be welded(a)	Postweld condition(b)	Ease of welding						Strength(c)						Ductility(d)						Corrosion resistance(e)					
		Filler alloys																							
		2319	4043	4145	5039	5556(f)	5554(g)	2319	4043	4145	5039	5556(f)	5554(g)	2319	4043	4145	5039	5556(f)	5554(g)	2319	4043	4145	5039	5556(f)	5554(g)
To weld 2014 or 2024 to:																									
2014, 2024 or 2219	X	C	B	A	–	–	–	A	B	A	–	–	–	A	A	B	–	–	–	A	B	B	–	–	
	Y	C	B	A	–	–	–	A	C	B	–	–	–	A	B	B	–	–	–	A	B	B	–	–	–
To weld 2219 to:																									
2219	X	A	A	A	–	–	–	A	B	B	–	–	–	A	B	B	–	–	–	A	B	B	–	–	
	Y or Z	A	A	A	–	–	–	A	C	B	–	–	–	A	B	B	–	–	–	A	B	B	–	–	–
To weld 6061, 6063 or 6101 to:																									
1100	X	–	A	–	–	B	–	–	A	–	–	A	–	–	B	–	–	A	–	–	A	–	–	B	–
2014 or 2024	X	–	B	A	–	–	–	–	A	A	–	–	–	–	A	B	–	–	–	–	A	A	–	–	–
2219	X	–	A	A	–	–	–	–	A	A	–	–	–	–	A	B	–	–	–	–	A	A	–	–	–
3003, 3004, 5005 or 5050	X	–	A	–	–	B	–	–	B	–	–	A	–	–	B	–	–	A	–	–	A	–	–	B	–
5052, 5154 or 5454	X	–	A	–	–	B	C	–	C	–	–	A	B	–	B	–	–	A	A	–	A	–	–	B	A
5083, 5086 or 5456	X	–	–	–	–	A	B	–	–	–	–	A	B	–	–	–	–	B	A	–	–	–	–	A	A
6061, 6063 or 6101	X	–	A	–	–	B	C	–	C	–	–	A	B	–	B	–	–	A	A	–	A	–	–	C	B
	Y or Z	–	A	–	–	(h)	B	–	A	–	–	(h)	B	–	B	–	–	(h)	A	–	A	–	–	(h)	B
To weld 7005 or 7039 to:																									
5052, 5154 or 5454	X	–	A	–	A	A	B	–	D	–	A	B	C	–	B	–	A	A	A	–	B	–	A	A	A
5083, 5086 or 5456	X	–	–	–	A	A	–	–	–	–	A	B	–	–	–	–	A	A	–	–	–	–	A	A	–
6061 or 6063	X	–	A	–	A	A	B	–	D	–	A	B	C	–	B	–	A	A	A	–	A	–	A	A	A
	Y or Z	–	A	–	A	(h)	B)	–	C	–	A	(h)	B	–	B	–	A	(h)	A	–	A	–	A	(h)	A
7005 or 7039	X	–	–	–	A	A	–	–	–	–	A	B	–	–	–	–	A	A	–	–	–	–	A	A	–
	Y or Z	–	–	–	A	(h)	–	–	–	–	A	(h)	–	–	–	–	A	(h)	–	–	–	–	A	(h)	–
To weld 7075 or 7178 to:																									
7075 or 7178	X	–	A	A	B	B	–	–	C	C	A	B	–	–	B	B	A	A	–	–	B	B	A	A	–
	Y or Z	–	A	A	B	(h)	–	–	B	B	A	(h)	–	–	B	B	A	(h)	–	–	A	A	B	(h)	–

(a) Ratings for both bare and alclad materials are the same. (b) X = naturally aged for 30 days or longer; Y = postweld solution heat treated and artificially aged; Z = postweld artificially aged. (c) Ultimate strength from cross-weld tensile test. (d) Ratings based on free-bend elongation of weld. (e) Ratings based on continuous or alternate immersion in fresh or salt water. (f) 5183 and 5356 have the same ratings as 5556. (g) Filler alloy 5554 is suitable for welding 6061, 6063 and 7005 prior to brazing. (h) Filler alloy not recommended because of possible susceptibility to stress-corrosion cracking when postweld heat treated.



Solution Number	Solution Type	Composition	Operating temperature, F	Immersion time, minutes
1	Nonsilicated alkaline cleaner	3 to 4 oz/gal of water	140 to 150	5 to 10
2	Caustic soda etch	3 to 4 oz/gal of water	145 to 150	4 to 6
3	Cold water rinse	Water(a)	70	1 to 3
4	Chromic acid deoxidizer	11 to 13 oz/gal of water	70 to 90	6 to 10
5	Warm water rinse	Water(b)	135 to 145	1(c)

(a) Rinse should be overflowing, with air agitation. (b) Rinse should be overflowing, to remove the acid and warm the part for quick drying. (c) Minimum.

Fig. 3. Flow chart for five-step cleaning process used for parts to be welded to make a fuel-storage tank (Example 293)

Example 293. Preweld Cleaning of Parts for Fuel-Storage Tanks (Fig. 3)

Preweld cleaning required special attention in the fabrication of fuel-storage tanks for M-60 combat tanks from 80 individual parts, because the welded joints had to have optimum ductility and fatigue strength to withstand the severe vibrational stress to which the fuel-storage tanks were subjected in service.

Original preweld cleaning practice called for: (*a*) vapor degreasing (when necessary) to remove most of the foreign matter; (*b*) dipping in a caustic etching solution; (*c*) rinsing; (*d*) dipping in a nitric acid deoxidizing solution; and (*e*) rinsing. This method of cleaning, however, was unsatisfactory because:

1. The metal surfaces reoxidized after a few hours, which necessitated the recleaning of many parts and subassemblies during the welding of a tank.
2. During the caustic etch, the amount of metal removed from threaded parts was enough to cause the threads to be out of tolerance.
3. Use of nitric acid created a safety hazard.

A special chemical cleaning method consisting of five steps was therefore developed. The process is shown in Fig. 3 and described in the accompanying table. Parts with drawing compound or heavy soils were vapor degreased prior to step 1.

To prevent contamination of the chemical solutions, back rinsing was not permitted. Solution strengths were checked daily by titration and were kept in the composition ranges listed in the table.

Work metal was ⅛-in.-thick alloy 5086-H32 sheet, alloy 5083-H112 extrusions, and alloy 6061-T6 fittings. The design of the vehicle utilized every available cubic inch of space between the engine and the tank hull, and in consequence the left-hand and right-hand fuel tanks, composed of 50 subassemblies (80 parts), were of dissimilar and complex shapes. Although the irregular shapes were formed, wherever possible, by bending, approximately 20 ft of gas metal-arc tack welding and 200 ft of gas tungsten-arc welded seams were required per fuel tank. The details for tack welding are given in Example 305; joint-welding details are given in Example 311.

The special precleaning method produced a more stable surface on the aluminum alloy parts, which permitted a longer elapsed time between cleaning and welding, and permitted, under normal conditions,

complete welding of an assembly without recleaning. Solution 2 was bypassed when parts that were to be cleaned contained threads (as the etchant affected thread dimensions) and when recleaning was required for dusty parts and parts whose welding had been delayed.

Chemical recleaning could not be used on the subassemblies before final welding of the assembly because capillary action would have caused entrapment of reagents in the seams on some of the parts, which would have caused sputtering during welding. Therefore, these joints were recleaned mechanically with power brushes having stainless steel wire bristles.

Preheating

In gas-shielded arc welding of aluminum alloys, preheating of parts to be welded is normally employed only when the temperature of the parts is below 15 F or when the mass of the parts is such that the heat is conducted away from the joint faster than the welding process can supply it. Preheating may be advantageous for gas tungsten-arc welding with alternating current of parts thicker than about 3/16 in. and gas metal-arc welding of parts thicker than about 1 in. Gas tungsten-arc welding with reverse-polarity direct current is limited to thin material, and preheating is not necessary with this process. It is also not necessary to preheat thick parts when gas tungsten-arc welding using straight-polarity direct current, because of the high heat input provided to the work.

Preheating can also reduce production costs because the joint area will reach welding temperature faster, thus permitting higher welding speeds.

Various methods can be employed to preheat the entire part or assembly to be welded, or only the area adjacent to the weld can be heated by use of a gas torch. In mechanized welding, local preheating (and drying) can be done by gas or tungsten-arc torches installed ahead of the welding electrode.

The preheating temperature depends on the job. Often 200 F is sufficient to ensure adequate penetration on weld starts, without readjustment of the current as welding progresses. Preheating temperature for wrought aluminum alloys seldom exceeds 300 to 400 F, because the desirable properties of certain aluminum alloys and tempers may be adversely affected at higher temperatures. Aluminum-magnesium alloys containing 4.0 to 5.5% Mg (5083, 5086 and 5456) should not be preheated to between 200 and 450 F, because their resistance to stress-corrosion cracking will be reduced by this treatment.

Large or intricate castings should be preheated to approximately 800 F to minimize thermal stresses and to facilitate attainment of the welding temperature. After welding, such castings should be cooled slowly to minimize the danger of cracking. Castings that are to be used in the heat treated condition should be welded before heat treatment or should be reheat treated after welding. Preheating (and the heat of welding) may affect the corrosion resistance of some alloys — for instance, alloy 220 — unless welding is followed by heat treatment.

Preheating for weld repair of a plate is described in Example 307, and for a casting on page 318.

Fixtures

Design of fixtures is based on the expectation that dimensional changes in welding aluminum alloys will be twice as great as in the welding of steel. The coefficient of expansion of aluminum is about twice that of steel, and its melting point is about half that of steel. Thus, the change in dimensions from welding heat is in the same range as that for steel. However, the thermal conductivity of aluminum is greater. In general, the amount of expansion is inversely proportional to the speed of welding.

When butt welding aluminum sheet, the fixture should enable the sheet to be clamped with a uniform force of approximately 200 lb per linear inch of

Table 7. Typical Conditions for Welding Corner Joints by the Semiautomatic Gas Metal-Arc Process

Metal thickness, in.	Welding position(a)	Electrode wire: Diameter, in.	Electrode wire: Used per 100 ft, lb	Argon flow, cfh	Arc: Current (dcrp), amp	Arc: Voltage, v	Welding: Speed, ipm	Welding: Number of passes
1/8	F	3/64	2	30	110	20	30	1
	H, V	3/64	2	30	100	20	24	1
	O	3/64	2	40	100	20	24	1
3/16	F	3/64	4½	30	170	20	30	1
	H, V	3/64	4½	35	150	20	24	1
	O	3/64	4½	40	160	20	24	1
1/4	F	1/16	7	40	200	25 to 29	30	1
	H, V	1/16	7	45	170	25 to 29	24	1
	O	1/16	7	50	180	25 to 29	24	1
3/8	F	1/16	17	50	250	25 to 29	30	3
	H, V	1/16	17	50	170	25 to 29	24	3
	O	1/16	17	60	180	25 to 29	24	3
1/2	F	3/32	30	50	290	25 to 31	16	3
	H, V	1/16	30	50	190	25 to 29	12	3
	O	1/16	30	70	200	25 to 29	18	5
3/4	F	3/32	66	60	310	25 to 31	16	4
	H, V	1/16	66	60	220	25 to 29	8	4

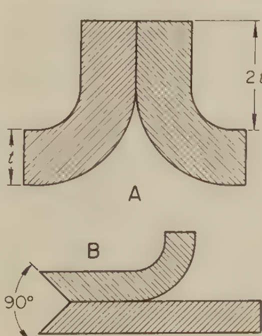
(a) F = flat; H = horizontal; V = vertical; O = overhead

Table 8. Typical Conditions for Welding T and Lap Joints by the Semiautomatic Gas Metal-Arc Process

Metal thickness, in.	Welding position(a)	Electrode wire: Diameter, in.	Electrode wire: Feed, ipm	Electrode wire: Used per 100 ft, lb	Argon: Flow, cfh	Argon: Used per 100 ft, cu ft	Arc: Current (dcrp), amp	Arc: Voltage, v	Time per 100 ft, hr(b)	Welding: Speed, ipm	Welding: Number of passes
1/8	F	3/64	190	2	30	31	125	20	1.04	30	1
	H, V	3/64	180	2	30	33	115	20	1.10	24	1
	O	3/64	175	2	40	45	110	20	1.13	24	1
3/16	F	3/64	255	4½	30	55	190	20	1.75	24	1
	H, V	3/64	230	4½	35	70	165	20	1.94	20	1
	O	3/64	245	4½	40	75	180	20	1.82	20	1
1/4	F	1/16	195	7	40	80	225	25 to 29	2.01	24	1
	H, V	1/16	170	7	45	105	200	25 to 29	2.30	20	1
	O	1/16	170	7	50	115	200	25 to 29	2.30	20	1
3/8	F	1/16	275	17	50	175	300	25 to 29	3.45	30	3
	H, V	1/16	170	17	50	280	200	25 to 29	5.59	24	3
	O	1/16	195	17	60	290	220	25 to 29	4.87	24	3
1/2	F	3/32	145	30	60	305	340	25 to 31	5.09	16	3
	H, V	1/16	200	30	60	505	225	25 to 29	8.39	12	3
	O	1/16	205	30	60	655	230	25 to 29	8.18	18	5
3/4	F	3/32	160	66	60	610	375	25 to 31	10.15	16	4
	H, V	1/16	235	66	60	945	260	25 to 29	15.71	8	4
	O	1/16	250	66	80	1180	275	25 to 29	14.76	18	10
1	F	3/32	180	120	60	985	425	25 to 31	16.40	8	4
	H, V	1/16	235	120	80	1715	260	25 to 29	28.56	6	6
	O	1/16	265	120	80	2025	290	25 to 29	25.31	18	14

(a) F = flat; H = horizontal; V = vertical; O = overhead. (b) Based on 100% arc efficiency at electrode-wire feed shown.

Table 9. Typical Conditions for Welding Edge Joints by the Semiautomatic Gas Metal-Arc Process



Joint design	Metal thickness, in.	Welding position(a)	Electrode wire: Diameter, in.	Electrode wire: Used per 100 ft, lb	Argon flow, cfh	Arc: Current (dcrp), amp	Arc: Voltage, v	Welding: Speed, ipm	Welding: Number of passes
Joint Design A									
	1/8	F	3/64	4	30	110	20	30	1
		H, V	3/64	4	30	100	20	24	1
		O	3/64	4	40	100	20	24	1
	3/16	F	3/64	8	30	170	20	30	1
		H, V	3/64	8	35	150	20	24	1
		O	3/64	8	40	160	20	24	1
	1/4	F	1/16	15	40	200	25 to 29	30	1
		H, V	1/16	15	45	170	25 to 29	24	1
		O	1/16	15	50	180	25 to 29	24	1
Joint Design B									
	3/8	F	1/16	34	50	250	25 to 29	30	3
		H, V	1/16	34	50	170	25 to 29	24	3
		O	1/16	34	60	180	25 to 29	24	3
	1/2	F	3/32	60	50	290	25 to 31	16	3
		H, V	1/16	60	50	190	25 to 29	12	3
		O	1/16	60	70	200	25 to 29	18	5

(a) F = flat; H = horizontal; V = vertical; O = overhead

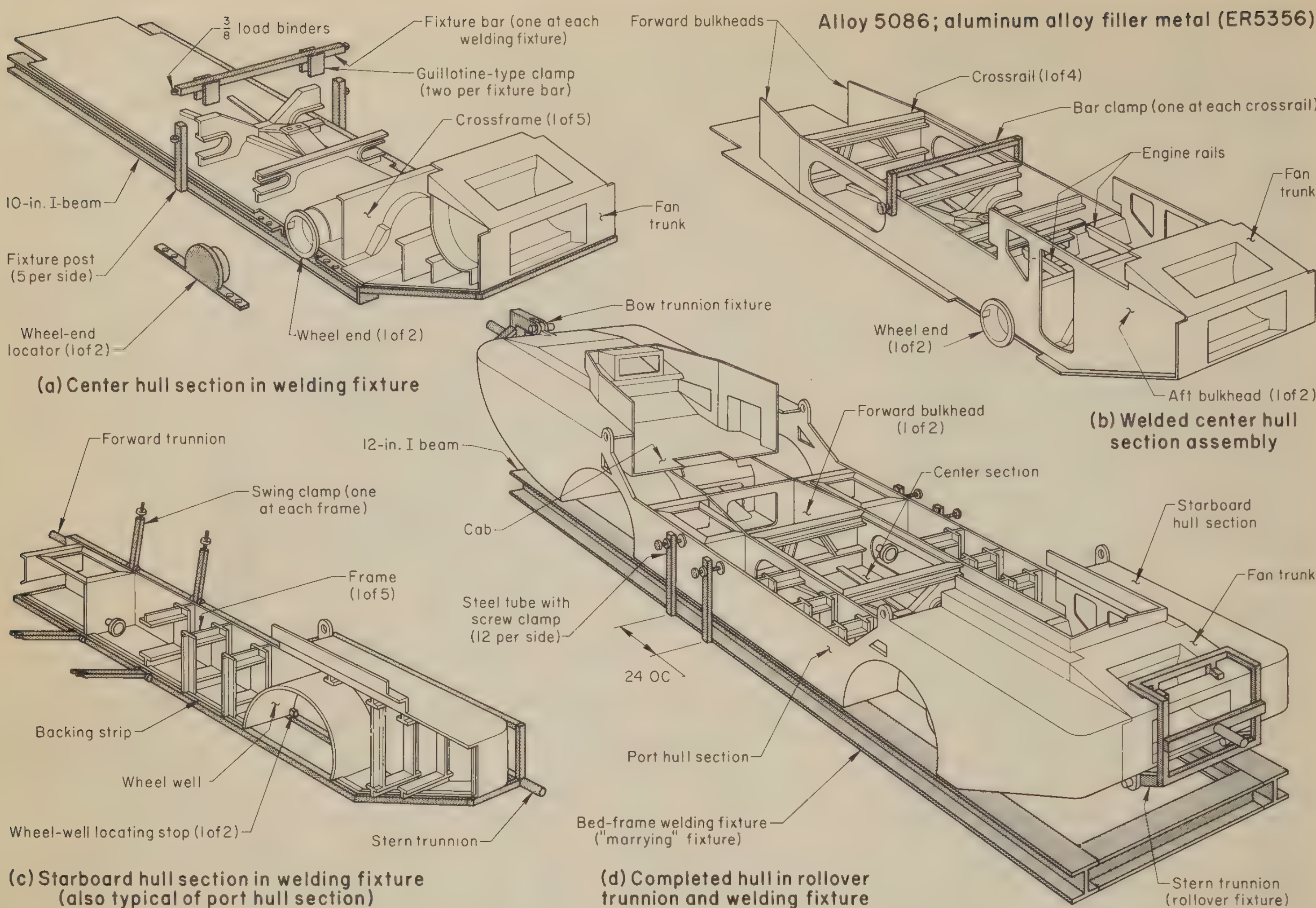


Fig. 4. Fixtures used for welding center hull section of an amphibious lighter to port and starboard hull sections (see also Example 297)

seam. This amount of force will usually ensure against movement of the sheet during welding. To guard against deflection of the arc, nonmagnetic materials, such as austenitic stainless steel, copper and aluminum, should be used for those parts of a fixture within 4 in. of the arc, and must be used for fixture parts within 2 in. of the arc.

Although rigid clamping reduces distortion, the inability of the weldment to contract, caused by the restraint, may induce residual stress as high as the yield strength of the base metal and may also result in cracking. To keep distortion to the minimum, the joint should be designed with minimum separation between members, and welding should be done in the minimum number of passes.

The several fixtures required for welding a 418-in.-long amphibious lighter are shown in Fig. 4. The fixtures included guillotine-type clamps for use with load binders, bar clamps, multiple swinging clamps, rollover trunnion adapters, I-beam bed plates with steel tubes around the outside edge (the basic "marrying" fixture), and screw clamps. The rollover feature was adopted to avoid out-of-position welding, as when a weld had to be made on the outside of the bottom of the hull. (Welding the center hull section to the port and starboard sections is described in Example 297.)

A fixture used in welding long pipelines is described in Example 298.

Because many aluminum alloy weldments incorporate extruded products, self-fixturing can often be employed. In the following example, the extrusions were designed so that the joints were self-aligning, thereby reducing both the assembly time and the cost of fixtures.

Example 294. Use of Extruded Shapes for Self-Alignment of Parts for Welding (Fig. 5)

By the use of self-aligning extruded shapes throughout, the modular instrument enclosure shown in Fig. 5 could be made as cheaply from aluminum as from steel. In this application, strength and seal-tightness were not important. Material costs were 60% higher for aluminum than for steel, but welding costs and overhead costs were lower, and less welding skill was needed. In addition, aluminum enclosures were lighter, required less maintenance, and had better corrosion resistance.

The enclosures were made of alloy 6061-T6. The roof, sides, base and doors were subassembled by means of interlocking mechanical joints, and then were assembled and welded only in strategic places, as shown in Fig. 5. The interlocking joints along the sides of the panel extrusions were left unwelded. The joints in the roof were calked with sealant, to make them dust-tight.

The self-aligning feature of the design can be seen in the corner detail in Fig. 5. A blank plate was used to maintain square alignment of the door opening.

Welding was done by the gas metal-arc process, using an electrode holder having an integral wire-feed drive from a 1-lb spool. The electrode holder, control unit, and power supply were a coordinated package. Initial voltage was set by the operator, and further adjustment was made by a wire-feed-rate dial on the electrode holder, which automatically adjusted welding current to the proper level. Additional information is given in the table with Fig. 5.

In later production, the original electrode holder was replaced by one having a pull-type wire feed from a 10-lb spool that was separate from the electrode holder. By using 10-lb spools instead of 1-lb spools, wire cost was reduced by approximately $1 per pound.

Electrode-wire selection was important from the standpoint of color match, because completed enclosures were not painted. ER4043 and some other electrode wires darkened in service. Preferred electrode was ER5154 wire having a bright finish, but ER5356 also met the color-match requirements and was used later.

Precleaning was not required, because the material was sufficiently clean and free of oil in the as-received condition.

Gas Metal-Arc Welding

The ability of gas metal-arc welding to deposit large quantities of weld metal in a short period of time has played a large part in the increased use of aluminum since the late 1940's. Typical conditions for gas metal-arc welding of aluminum alloys are given in Tables 7 through 10. Figure 6 shows

butt-joint designs for the conditions given in Table 10.

Thicknesses of aluminum alloys commonly joined by gas metal-arc welding range from ⅛ in. up to the maximum plate thickness available (several inches). In this thickness range, gas metal-arc welding is capable of high-quality weld deposits — for example, those meeting requirements of the ASME Boiler and Pressure Vessel Code. With the use of pulsed-current power supplies, some types of joints can be gas metal-arc welded in aluminum as thin as 0.030 to 0.040 in.

Welding speeds up to 55 in. per minute are obtained with semiautomatic welding, and speeds for machine and automatic welding can be as high as 180 in. per minute. Maximum welding speeds commensurate with the application are always desirable when welding aluminum alloys. The rapid cooling after welding, which results from high welding speeds, produces fine-grain weld deposits and retards the formation of low-melting constituents at the grain boundaries.

Power Supply and Equipment. Only reverse-polarity direct current (electrode positive), which gives good penetration and a cathodic cleaning action at the work surface, is used in gas metal-arc welding of aluminum alloys. The steady and pulsed direct-current power supplies, and the wire-feed systems, electrode holders, and control systems used for gas metal-arc welding of aluminum alloys, are the same as those used for gas metal-arc welding of other metals (see the article on Gas Metal-Arc Welding, on page 78). Push-type wire-feed systems can handle aluminum wire down to 0.045 in. in diameter, but for smaller wires, a pull-type or a push-pull system must be used. Grooved drive rolls are preferred; knurled rolls and serrated rolls are likely to chip off small particles of metal, which can enter the wire conduit and slow down or stop wire feed. Wire conduits, inlet guides, guide liners, and bushings for aluminum electrode wire should be of all-nylon or all-Teflon construction.

Shielding Gases for Gas Metal-Arc Welding

Argon, helium, and mixtures of the two, are used as shielding gases in gas metal-arc welding of aluminum alloys. Table 11 lists the preferred gases for various thicknesses of aluminum alloy to be welded.

Argon is generally preferred when welding thinner metal, mainly because of its lower arc heat. In addition, argon results in a smoother and more stable arc than helium, and thus much less weld spatter is obtained.

Helium, because of its greater arc heat, is capable of producing the deep penetration desirable in weld deposits in thicker metal. The bead profile with helium shielding is wider and less convex than with argon shielding, and the penetration pattern has a broader underbead. Welding with pure helium produces welds of darker appearance with some spatter. Helium is lighter than argon, requires higher flow rates, and it is more expensive. Therefore, helium is seldom used alone. However, in some jobs the use of higher currents, higher welding speeds and fewer passes can more than compensate for the higher cost of helium.

Argon-Helium Mixtures. To take advantage of the higher arc heat of helium without the disadvantages associated with using the pure gas, mixtures of argon and helium are usually used for out-of-position welding and in joining thick metal. Although users have individual preferences, mixtures ranging between 25 and 75% helium are most widely used. A helium-rich mixture, such as 75% helium and 25% argon, is frequently employed when welding workpieces more than 2 in. thick and is usually employed for out-of-position gas metal-arc welding. For workpieces more than 3 in. thick, helium-rich mixtures will maximize weld penetration and minimize porosity. When welding workpieces 1 to 3 in. thick in the flat position, increasing the current or voltage, or both, enables the helium content to be decreased.

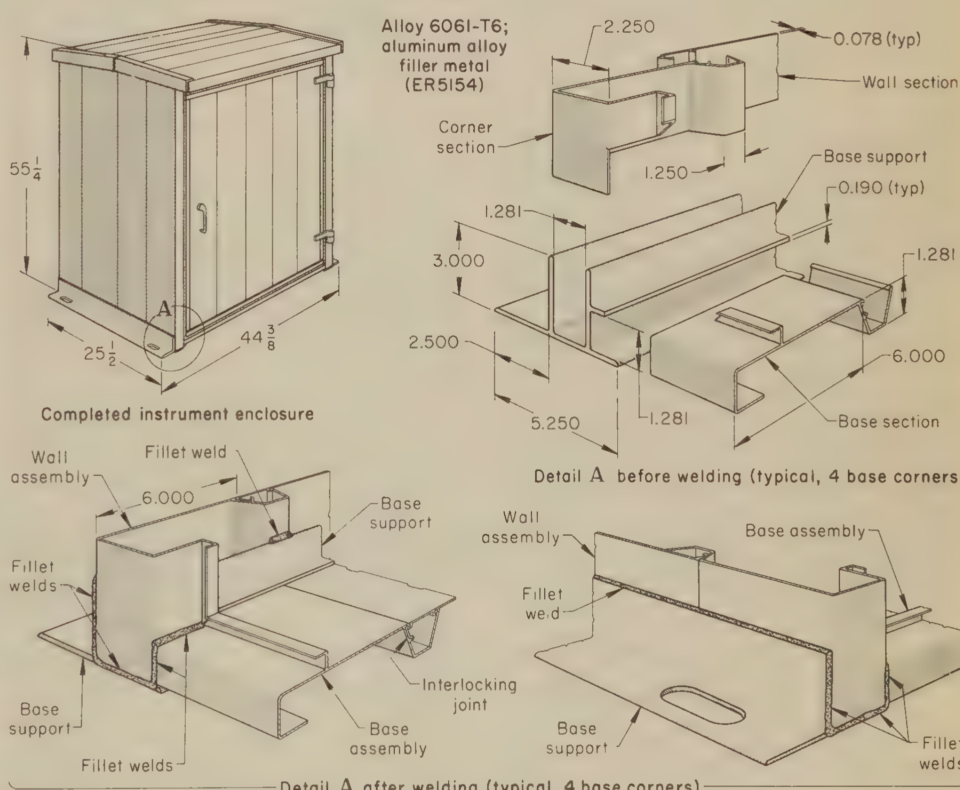
Oxygen Additions. Small percentages of oxygen are sometimes added to pure argon or to argon-helium mixtures. For some jobs they have been found to improve arc stability and make out-of-position welding easier. For example, in out-of-position welding thin sheet of alloys 1100 and 3003, a small amount of oxygen added to the argon shielding gas was found to improve solidification of the weld puddle. A drawback to the addition of oxygen to the shielding gas is that the welds are likely to contain a larger amount of entrapped oxide.

Nitrogen shielding gas plus a small amount of argon introduced separately through the contact-tube bore of the electrode holder results in an extremely hot, penetrating arc and has been used to produce welds of lowest cost and adequate strength and quality in EC electrical bus conductor.

Flow Rates. Typical shielding-gas flow rates for gas metal-arc welding of aluminum and aluminum alloys are given in Table 12. Note that helium requires about twice the flow of argon. The rate should not be greater than that which will have laminar flow.

Arc Characteristics in Gas Metal-Arc Welding

Increasing the welding current from low to high changes the arc from one producing short-circuiting metal transfer to one producing globular metal transfer and then to one producing spray metal transfer (see Fig. 2, page 79, in the article on Gas Metal-Arc Welding). Spray transfer produced by



Conditions for Semiautomatic Gas Metal-Arc Welding

Joint types	T, lap	Electrode wire	0.035-in.-diam ER5154(a)
Weld type	Fillet	Shielding gas	Argon, at 20 cfh
Power supply	200-amp, constant-voltage transformer-rectifier	Electrode stickout	¼ in.
		Current	130 amp, dcrp
Wire-feed system	Adjustable speed	Voltage	24 v
Electrode holder	200 amp, air cooled	Number of passes	One

(a) ER5154 is a former AWS classification that has been replaced by ER5654. ER5356, which met color-match requirements as well as ER5154, was used in later production.

Fig. 5. Modular instrument enclosure fabricated of extruded aluminum shapes. Note the self-aligning feature of the assembly. (Example 294)

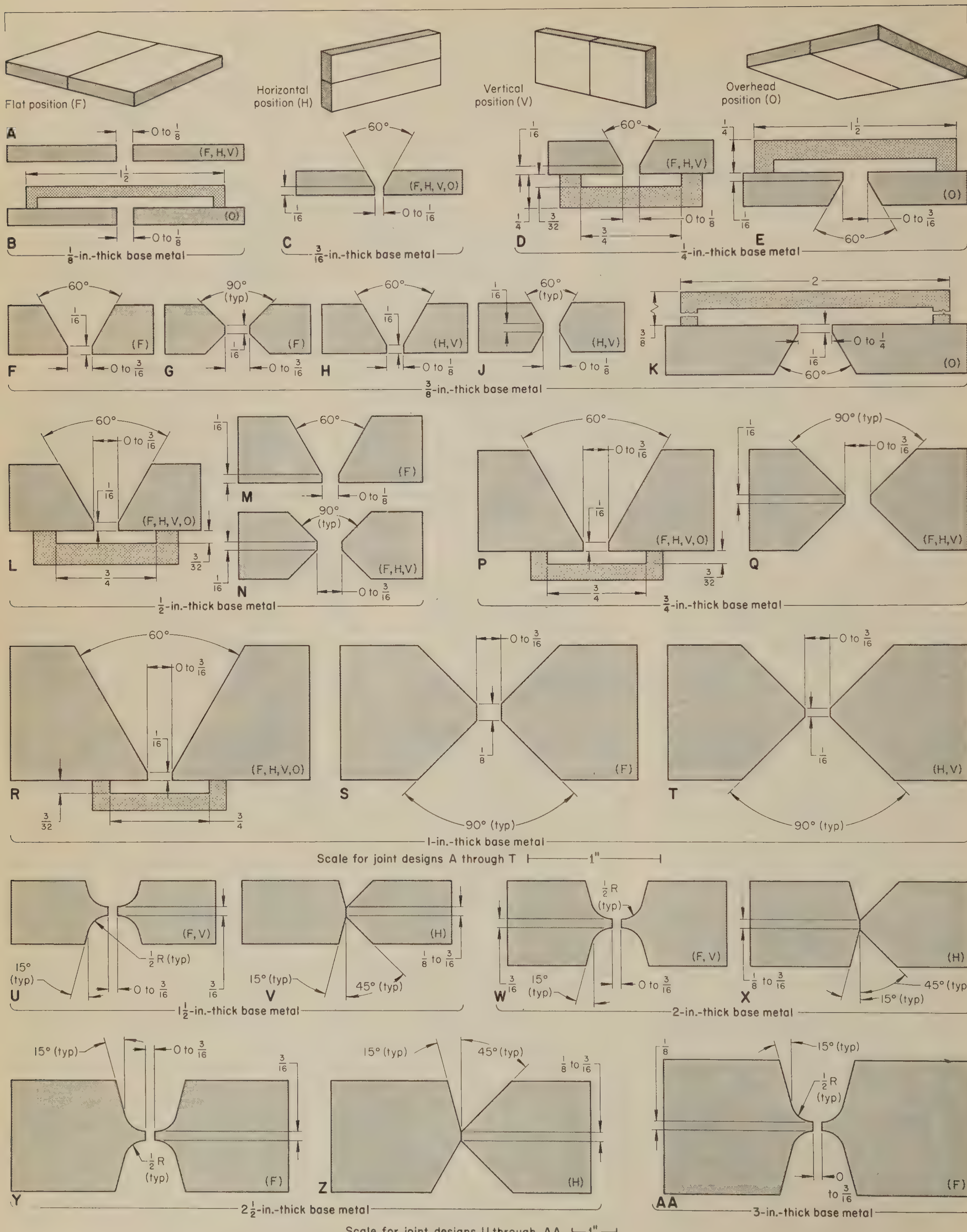


Fig. 6. Butt-joint designs for which applicable welding conditions are given in Table 10

either a steady-current arc or by a pulsed-current arc is used for almost all gas metal-arc welding of aluminum alloys. In some special applications, globular transfer and steady current are used instead.

To obtain spray metal transfer from steady-current arcs requires extremely high current densities when welding aluminum alloys. It is not uncommon to employ current densities ranging from 50,000 to 300,000 amp per square inch of electrode cross section. In contrast, current densities for gas tungsten-arc welding of aluminum alloys and for gas metal-arc welding of steel are about 10,000 amp per square inch.

The steady-current and current-density ranges in which the transition from globular to spray transfer takes place depend on the electrode size and the arc voltage employed. For a 3⁄64-in.-diam electrode and 22 to 31 volts, the change in type of transfer occurs at about 120 amp, or about 70,000 amp per square inch. Increasing the electrode diameter to 3⁄32 in. increases the transition current to about 220 amp, but decreases the current density to about 30,000 amp per square inch. When electrode diameters are larger than standard, the current density for the transfer transition is further reduced. The steady currents and wire-feed rates at which transfer transition takes place for electrodes of standard sizes are shown in Fig. 7. Pulsed currents must be used in order to achieve spray transfer at lower average currents and wire-feed rates.

Spray Transfer. Two of the notable characteristics of the spray-transfer arc are its stiffness and its narrowness; these advantages are described below:

Arc Stiffness for Deep Penetration. There is no lack of weld penetration when using spray transfer. Even in the low range of welding currents, the use of high current density and small-diameter electrode wire establishes a stable arc column with a well-defined pattern on the workpiece. To ensure fusion at the root of a butt joint, a minimum amount of root reinforcement is required, usually 1⁄32 to 3⁄16 in., depending on metal thickness and joint design.

Arc Stiffness for Out-of-Position Welding. When using spray transfer, the transfer follows the direction in which the electrode wire is pointed, which makes this type of transfer suitable for out-of-position welding. It can be an advantage when complicated parts require welding in several positions, such as in Examples 297 and 305. Spray transfer is also used to make a circumferential weld around a part too large to rotate, such as the welding of pipeline in Example 298.

Arc Narrowness for Small Fillet Welds. The spray arc has a narrow stable core, which concentrates the heat. This property enables fully fused small fillet welds to be made in relatively thick material.

In one application, corner joints having a minimum amount of weld metal and a minimum heat-affected zone were welded in thick alloy 5083 plate at minimum welding cost. Two basic joints were developed for near-minimum penetration (Fig. 8). Either a constant-current or a constant-voltage heavy-duty power supply was used, along with a heavy-duty wire-feed system and a water-cooled electrode holder. The electrode wire was 3⁄32-in.-diam ER5356. This wire size was chosen because the base metal was thick enough to prevent melt-through, it cost less per pound than smaller-diameter wire, and it was the largest diameter that could be deposited in all positions with semiautomatic equipment.

Table 10. Typical Conditions for Semiautomatic Gas Metal-Arc Welding of Butt Joints of Designs Shown in Fig. 6

			Electrode wire			Argon		Arc			Welding	
Metal thickness, in.	Joint design (see Fig. 6)(a)	Welding position (b)	Diameter, in.	Feed, ipm	Used per 100 ft, lb	Flow rate, cfh	Used per 100 ft, cu ft	Current (dcrp), amp	Voltage, v	Time per 100 ft, hr(c)	Speed, ipm	Number of passes
1⁄8	A	F	3⁄64	175	2	30	34	110	20	1.14	24	1
	A	H, V	3⁄64	170	2	30	35	100	20	1.17	24	1
	B	O	3⁄64	170	2½	40	58	105	20	1.46	24	1
3⁄16.....	C	F	3⁄64	235	4½	30	57	170	20	1.90	24	1
	C	H, V	3⁄64	215	4½	35	75	150	20	2.08	20	1
	C	O	3⁄64	225	5	40	90	160	20	2.21	18	1
1⁄4	D	F	1⁄16	170	8	40	105	200	25	2.63	24	1
	D	H, V	1⁄16	150	8	45	255	170	25	2.98	24	3
	E	O	1⁄16	160	10	50	175	180	29	3.49	24	3
3⁄8	F	F	1⁄16	265	18	50	190	290	25	3.80	24	2
	G	F	1⁄16	250	15	50	170	275	29	3.35	24	2
	H	H, V	1⁄16	160	18	50	315	190	25	6.29	24	2
	J	H, V	1⁄16	150	15	50	280	170	29	5.29	24	2
	K	O	1⁄16	170	23	50	380	200	25-29	7.56	24	5
1⁄2	L	F	3⁄32	130	31	50	295	290	25-31	5.87	16	2
	M	F	3⁄32	140	30	50	265	320	25-31	5.27	16	2
	N	F	3⁄32	130	29	50	275	300	25-31	5.49	16	3
	L	H, V	1⁄16	...	31	50	...	215	25-29	...	12	3
	N	H, V	1⁄16	160	29	50	505	190	25-29	10.13	12	2
	L	O	1⁄16	200	31	80	695	225	25-29	8.66	18	8
3⁄4	P	F	3⁄32	150	62	60	610	350	25-29	10.17	16	4
	Q	F	3⁄32	145	72	60	735	330	25-29	12.22	16	4
	P	H, V	1⁄16	225	62	60	925	250	25-29	15.47	8	4
	Q	H, V	1⁄16	215	72	60	1125	240	25-29	18.71	8	4
	P	O	1⁄16	225	62	80	1235	250	25-29	15.42	18	12
1	R	F	3⁄32	170	105	60	910	400	25-31	15.20	12	4
	S	F	3⁄32	165	85	60	760	380	25-31	12.68	12	6
	R	H, V	1⁄16	225	105	60	1565	250	25-29	26.11	6	4
	T	H, V	1⁄16	215	95	60	1480	240	25-29	24.69	6	6
	R	O	1⁄16	250	105	80	1880	275	25-29	23.48	18	15
1½	U	F	3⁄32	180	200	80	2185	425	25-31	27.33	12	10
	V	H	1⁄16	255	105	80	1840	280	25-31	23.02	24	24
	V	H	3⁄32	150	105	80	1380	350	25-31	17.22	24	14
	U	V	1⁄16	225	200	80	3980	260	25-31	49.73	24	20
	U	V	3⁄32	145	200	80	2715	330	25-31	33.93	24	12
2	W	F	3⁄32	180	335	80	3665	425	25-31	45.79	12	12
	X	H	1⁄16	215	185	80	3845	245	25-31	48.08	24	30
	X	H	3⁄32	170	185	80	2140	425	25-31	26.78	24	24
	W	V	1⁄16	215	300	80	6240	240	25-31	77.97	20	26
	W	V	3⁄32	150	300	80	3935	350	25-31	49.19	20	15
2½	Y	F	3⁄32	180	350	80	3825	425	25-31	47.83	12	14
	Z	H	1⁄16	215	270	80	5615	245	25-31	70.18	24	32
	Z	H	3⁄32	150	270	80	3540	350	25-31	44.27	24	26
3	AA	F	3⁄32	190	500	80	5180	450	25-31	64.77	20	30

(a) Letters refer to joint designs in Fig. 6. When joint designs V, X and Z are used in the horizontal welding position, the 15° bevel should be on the bottom plate. (b) F = flat; H = horizontal; V = vertical; O = overhead. (c) Based on 100% arc efficiency at electrode-wire feed shown.

Very small fillet welds can be made in thinner workpieces, such as between the 1⁄4-in.-thick liner ring and the 1⁄8-in.-thick truncated cone shown in Fig. 9. In this application, using 3⁄64-in.-diam ER5183 electrode wire, it was not difficult for the welding operator to maintain a small weld bead and thus to hold to a minimum any distortion that could have taken place had the weld been larger.

Arc Narrowness for Square-Groove and Narrow-Groove Butt Joints (High-Current-Density Welding). The concentrated heat of the spray arc can also be used to weld butt joints with square or narrow grooves, thus reducing the amount and cost of the electrode wire required to make the joint.

Techniques have been developed to extend the usable current densities into the high range (to 300,000 amp per square inch), to take advantage of the very narrow penetrating arc. (At these high current densities, the characteristic hissing noise of the arc is replaced by a crackling noise.) These techniques are especially suitable

Table 11. Shielding Gases and Gas Mixtures Commonly Used for Gas Metal-Arc Welding of Aluminum Alloys

Work-metal thickness, in.	Shielding gas or mixture
0 to 3⁄4	100% argon
3⁄4 to 2	100% argon
	75% argon, 25% helium
	50% argon, 50% helium
2 to 3	50% argon, 50% helium
	25% argon, 75% helium
Over 3	25% argon, 75% helium

Table 12. Typical Shielding-Gas Flow Rates for Gas Metal-Arc Welding of Aluminum Alloys(a)

Shielding gas	Flow rate, cfh(b)
100% argon	30 to 70
75% helium, 25% argon	50 to 110
100% helium	60 to 140

(a) Using 1⁄16-in.-diam electrode wire. (b) The lower rates are more suitable for indoor work and moderate welding current. The higher rates are more suitable for high current, maximum speed, and outdoor welding.

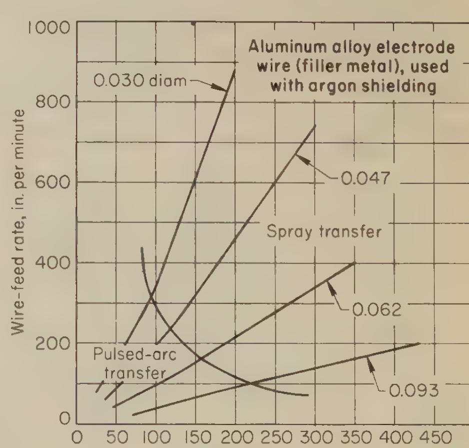


Fig. 7. Effect of wire-feed rate and welding current for various sizes of electrode wires in gas metal-arc welding. Note transition from pulsed-arc to spray transfer.

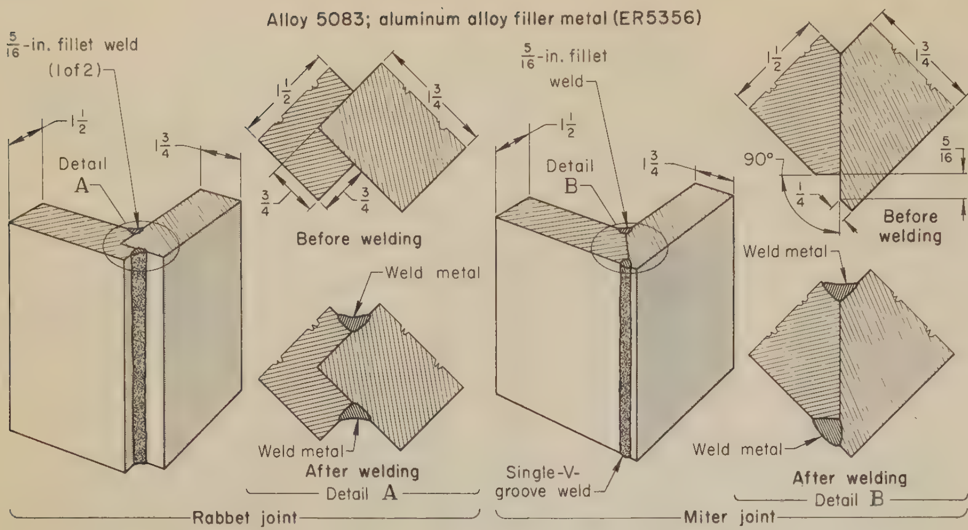


Fig. 8. Corner joints with small fillet and groove welds made by gas metal-arc welding

Table 13. Typical Conditions for High-Current-Density Welding of Square-Groove Butt Joints by the Automatic Gas Metal-Arc Process

Plate thickness, in.	Electrode wire: Diameter, in.	Electrode wire: Feed (approx), ipm	Argon flow, cfh	Arc: Current (dcrp), amp	Arc: Voltage, v	Welding: Speed, ipm	Welding: Number of passes
¼	3/32	170	80	370	24	23	1
¼	1/16	240	60	280	23 to 24	35	2
⅜	3/32	200	80	420	24 to 25	18	1
⅜	3/32	155	80	350	24 to 25	28 to 30	2
½	3/32	210	100	450	25	14 to 15	1
½	3/32	205	80	430	25	23	2
½	⅛	125	100	450	25	14 to 15	1
⅝	3/32	205	80	430	25	18	2
¾	3/32	210	100	450	25 to 26	16	2
¾	⅛	125	100	450	25 to 26	16	2
1	3/32	240	100	500	25 to 26	10 to 12	2
1	⅛	135	100	500	25 to 26	10 to 12	2
1¼	⅛	145	100	550	26	8 to 10	2
1½	9/64	130	100	590	26	8	2

when making square-groove butt joints in base metal from ¼ to ⅝ in. thick. Welding is often accomplished in two passes, one from each side, at a much greater speed than is possible at lower current densities. Back gouging is rarely required, and welding in one pass instead of several stringer-bead passes greatly reduces the total heat input. The reduction in heat input results in less distortion and, in heat treatable alloys, produces better as-welded properties. Most welds made with the "square-butt" and "high-current" techniques are of better quality than standard radiographic requirements demand.

Thicknesses greater than ⅝ in. can also be welded with a square-groove butt joint, but the amount of reinforcement may be excessive. Where reinforcement must be minimized, V-grooves can be machined in both sides of the joint to the amount required. Figure 10 shows how two 1¾-in.-thick plates of alloy 5083 were joined, using only one pass from each side, with 450-amp welding current, 28 volts, 100 cu ft per hour of argon for shielding, and 1/16-in.-diam ER5356 electrode wire.

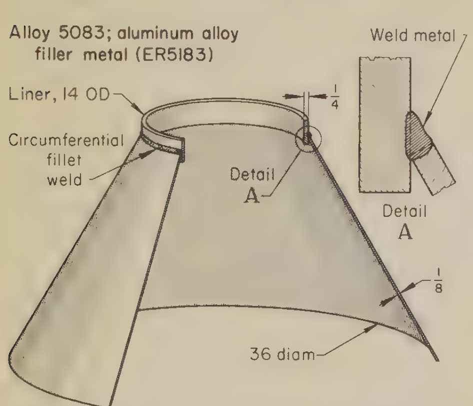


Fig. 9. Cone and liner ring that were joined by a small fillet weld to minimize distortion

The degree of bevel required with high-current-density welding is considerably less than with conventional welding. The root face is quite thick — usually about half the thickness of the plate. Joint preparation is not critical; machining need not be as accurate as for conventional joints.

Good results can be achieved with either a constant-current or a constant-voltage power supply. Argon should be supplied at 60 to 100 cu ft per hour, without excessive turbulence. The electrode holder and welding machine must have suitable current-carrying capacity. At present, high-current-density welding is normally used for automatic welding in the flat position where the welding conditions can be closely controlled. See Table 13 for conditions.

Table 14 presents the results obtained in tension and bend tests on single-V-groove joints made by conventional methods and typical square-groove butt joints made by high-current-density methods. The economic advantage of high-current-density welding with square grooves is evident.

Pulsed-arc transfer is a type of spray transfer that occurs in pulses at regularly spaced intervals. In the time interval between pulses, the welding current is reduced and no metal transfer occurs. The low average current and low heat input associated with pulsed-arc welding have allowed the advantages of spray transfer to be extended to the welding of sections thinner than can be spray-transfer welded using conventional steady-current power supplies. (Previously, short-circuiting transfer was used to gas metal-arc weld sheet of this lower thickness.)

In addition to enabling the spray-transfer welding of aluminum 0.030 to 0.125 in. thick, pulsed-arc transfer offers other advantages. One is the option of using larger-diameter electrode wires, which cost less per pound, are easier to feed, have fewer current-transfer problems in the contact tube, and have a lower probability of weld porosity from surface contamination on the wire because of the lower surface-to-volume ratio of the larger wire.

Another advantage is that sheet can be welded to heavier plate, even when the joint has a poor fit. A layer of metal is progressively built up on the thicker section until the gap is bridged.

Well-formed root beads and finishing beads are easily made on thin aluminum with pulsed-arc welding, whereas the beads made by short-circuiting transfer have high crowns, which consume more filler metal, can cause distortion due to the unbalanced cross section of single-pass welds, and have poor appearance. Also, adjusting welding conditions to obtain good fusion with short-circuiting transfer is difficult. This type of transfer has been largely replaced by pulsed-arc transfer.

Globular Transfer. The type of arc that produces metal transfer by a large drop of molten metal is seldom used when welding aluminum alloys because with conventional steady-current power supply the transfer is likely to be erratic. But, because the arc penetration is shallower and the heat input is lower at the current densities that produce this type of transfer, globular transfer has occasionally been used when welding metal thinner than that normally welded with spray transfer and steady current (⅛ in. and less).

Globular transfer was successfully employed in joining the side of about 1200 ft of 1-in.-OD, 0.065-in.-wall alloy 3003 tubing to the surface of ⅛-in.-thick alloy 3003 sheet with a single-flare bevel-groove weld. A steady current of 120 to 130 amp and a voltage of 19 to 19½ volts were used with a constant-voltage power supply, a shielding-gas mixture of 75% argon and 25% helium, and 0.020-in.-diam ER4043 electrode wire. Welding speed was 15 in. per minute, using manual manipulation of the electrode holder. Only two

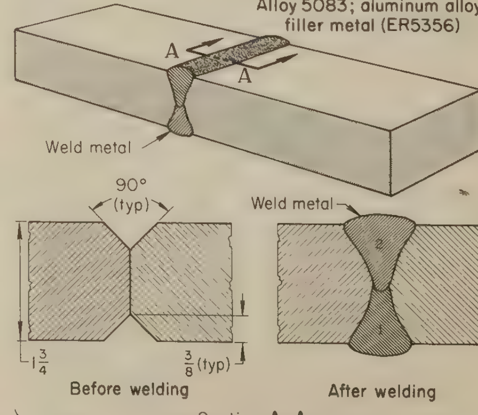


Fig. 10. Edge preparation for high-current-density welding of aluminum plate 1¾ in. thick, with one pass from each side

leaks, both caused by excessive melt-through, needed to be repaired.

Electrode Wires for Gas Metal-Arc Welding

Classifications and compositions of electrode wires are given in Table 3. Standard wire sizes are available in 1-lb and 10-lb spools in sizes from 0.030-in. to 0.040-in. diam and in 1-lb and 15-lb spools in sizes from 3⁄64-in. to 1⁄8-in. diam. Deposition and wire-feed rates obtained with two common electrodes in the standard sizes are shown in Fig. 11 for various welding conditions.

Electrode-wire feed should be selected so that the wire is consumed as fast as it emerges from the electrode holder, without extending more than 3⁄8 in. beyond the shielding-gas nozzle. The electrode holder is tilted not more than 10° forehand. The arc length that should be used is governed by the metal thickness, the type of joint, and the welding current. When making small fillet welds and welding narrow-groove butt joints, a short arc is preferred. Arc length is usually 1⁄8 to 3⁄8 in.

The wire size chosen for each application depends on the requirements and welding conditions for that application. The following example describes the successful semiautomatic gas metal-arc welding of one of the aluminum-copper alloys, using a fairly small-diameter electrode wire and a special joint design.

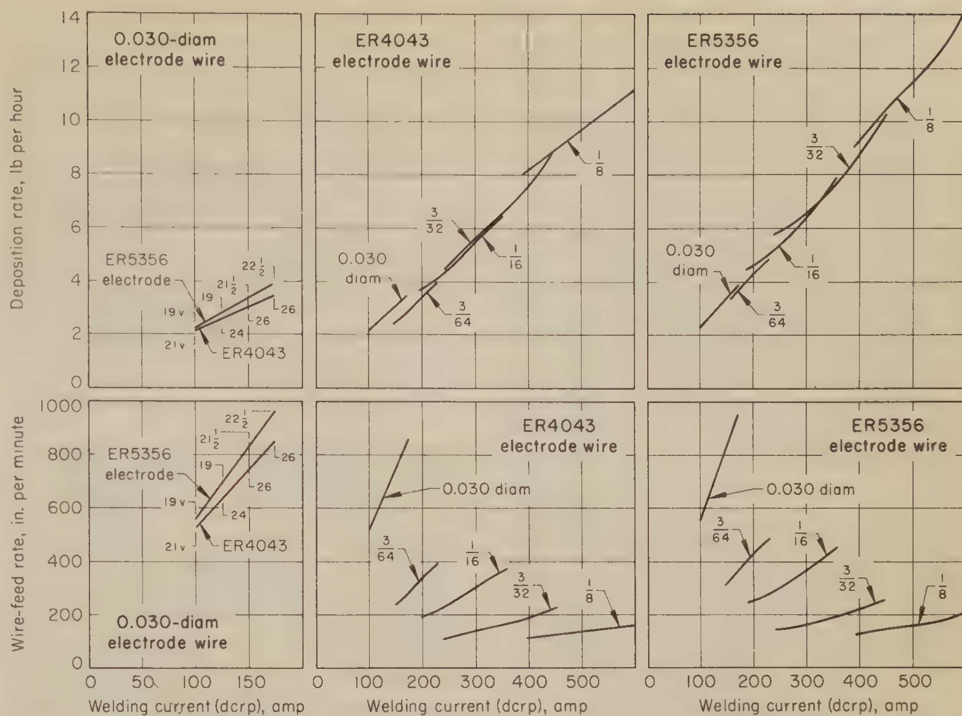


Fig. 11. Typical deposition rates and wire-feed rates for gas metal-arc welding with ER4043 and ER5356 electrode wire, under argon shielding

Example 295. Semiautomatic Gas Metal-Arc Welding of 1⁄4-In. 2014-T6 Plate, Using a "Step-Down" Joint and 3⁄64-In.-Diam Electrode Wire (Fig. 12)

Alloy 2014-T6 plate 1⁄4 in. thick was butt welded in two passes by semiautomatic gas metal-arc welding, using a special step-down joint, an electrode wire of smaller diameter, a helium-argon atmosphere, and a special backing insert.

The purpose of the step-down joint (Fig. 12) was to ensure uniform root penetration and a smooth contour on the root surface. This joint was superior to a V-groove joint because the arc produced by the conventional power supply used might have wandered on the groove face of a V-groove joint; this undesirable wandering does not occur in a step-down joint. A further advantage was the ease with which a uniform land could be machined into the plate edges.

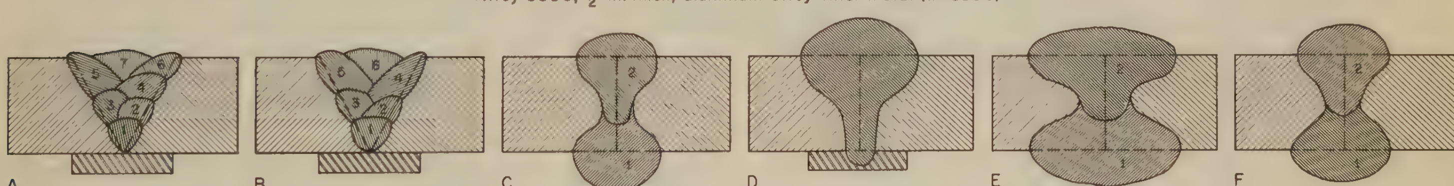
Use of the 3⁄64-in.-diam electrode wire, rather than the 1⁄16-in.-diam wire normally used with 1⁄4-in. plate, allowed a lower welding current while maintaining a high current density and a uniform metal transfer (spray type). The step-down joint enabled a relatively low welding current to be used for the root pass to avoid melt-through. The smaller-diameter wire also resulted in a more concentrated plasma cone and faster welding, which helped to reduce the width and severity of the heat-affected zone. The 3⁄64-in.-diam wire was used for both passes. ER4043 filler metal was chosen for its low crack sensitivity.

A 75% helium, 25% argon gas mixture was used for shielding, primarily so that the cover pass would be wider and the weld could be completed in two passes.

The weld backing bar contained a grooved insert that was made of either a metal with low thermal conductivity (such as stainless steel) or one with high thermal conductivity (such as copper), depending on the heat flow encountered in each

Table 14. Typical Test Results and Cost Factors for Gas Metal-Arc Welds in 1⁄2-In. Alloy 5356 Plate

Alloy 5356, $\frac{1}{2}$-in. thick; aluminum alloy filler metal (ER5356)



Item	Joint type (see illustration above): Single-V-groove butt A	B	C	Square-groove butt(a) D	E	F
Welding Conditions						
Operation	Automatic	Automatic	Automatic	Automatic	Automatic	Semiautomatic
Electrode wire	ER5356	ER5356	ER5356	ER5356	ER5356	ER5356
Electrode diameter, in.	1⁄16	1⁄16	3⁄32	3⁄32	3⁄32	1⁄16
Shielding gas	75% He, 25% A	Argon	Argon	Argon	75% He, 25% A	Argon
Current (dcrp), amp	275	290	400	450	400	350
Number of passes	7	6	2	1	2	2
Properties of Welds						
Tensile strength, psi	42,200	42,900	43,200	41,100	40,900	43,500
Elongation in 2 in., %	12.5	13.5	11.0	13.0	14.0	14.5
Bend test (number passed, number tested) (b):						
4t test	3 of 3	3 of 3	0 of 4	3 of 3	3 of 4	3 of 3
6⅔t test	4 of 4	1 of 1	1 of 1	....	....	....
Cost Factors						
Shielding gas, cu ft/ft of weld	7.9	2.7	1.4	1.3	4.1	1.4
Arc time, min/ft of weld	3.8	3.3	1.0	1.0	1.4	1.7
Electrode wire, lb/ft of weld	0.24	0.23	0.13	0.14	0.16	0.16

(a) High-current-density welding. (b) Standard is 6⅔t.

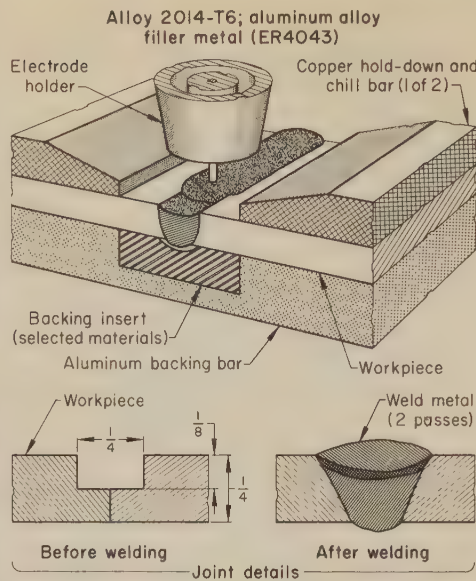
individual welding job. Use of a low-conductivity metal insert was likely to produce a smoother contour at the root surface than use of the high-conductivity metal insert. However, the risk of melt-through was somewhat greater when using the low-conductivity insert, and the cooling of the weld area was slower, which somewhat increased the width and severity of the heat-affected zone.

Before assembly for welding, joint surfaces were chemically cleaned by brush application of a commercial cleaner, wiping the joint clean, and then drying it with a clean cloth. After completion of the root pass, the face of the weld was cleaned with a rotary stainless steel wire power brush, in preparation for the cover pass.

Conditions for welding are given in the table that accompanies Fig. 12.

[In addition to the technique described above, pulsed-arc welding may be used with a V-groove joint to join ¼-in.-thick alloy 2014-T6 plate.]

As a rule, electrode wires from 0.030 to 3/32 in. in diameter are used with semiautomatic and automatic welding. The ⅛-in.-diam size is normally used only with automatic welding, as in the following application.



Semiautomatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Step-down groove
Joint tolerances	0.025-in. max root opening; ±0.005-in. max mismatch
Welding position	Flat
Power supply	500 amp, constant voltage
Fixtures	Copper hold-down and chill bars; aluminum backing bar with grooved insert
Electrode holder	500 amp, water cooled
Electrode wire	3/64-in.-diam ER4043
Shielding gas	75% helium, 25% argon, at 100 cfh
Number of passes	Two

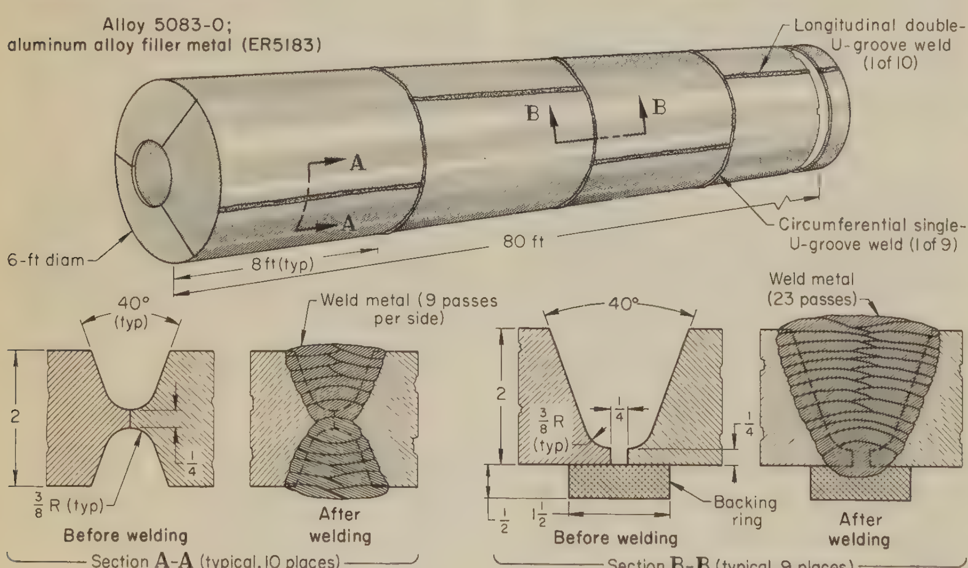
	First pass	Second pass
Current (dcrp), amp	215	140
Voltage, v	28	30
Welding speed, ipm	29	15

Fig. 12. Welding setup, showing special step-down joint design and backing bar with insert for varying cooling effect (Example 295)

Example 296. Use of ⅛-In.-Diam Electrode Wire and Automatic Welding To Decrease Welding Time for Large Heat Exchangers (Fig. 13)

Several heat exchangers, 6 ft in diameter and 80 ft long, were constructed by welding 2-in.-thick alloy 5083-O formed plate sections by the gas metal-arc process. Because of the size of the heat exchangers and the thickness of the metal, welding conditions that would keep welding time to the minimum were desirable.

Double-U grooves were machined on the plates for longitudinal welds, where welding could be done from both sides, and single-U grooves were machined for circumferential welds, where welding could be done from one side only. The single-U grooves were permanently backed with aluminum rings. Design of the two types of grooves is shown in Fig. 13.



Conditions for Automatic Gas Metal-Arc Welding

Joint type	Butt
Weld type:	
Longitudinal welds	Double-U groove
Circumferential welds	Single-U groove
Power supply	1000 amp, constant voltage
Electrode holder	800 amp, water cooled
Electrode wire	⅛-in.-diam ER5183
Shielding gas	75% A, 25% He, at 60 cfh
Welding position (all welds)	Flat
Current	460 to 480 amp, dcrp
Voltage	35 v
Welding speed	18 to 20 ipm
Number of passes, longitudinal welds	18
Number of passes, circumferential welds	23

Fig. 13. Heat exchanger that was welded by automatic gas metal-arc welding, joint design, and welding-pass sequence (Example 296)

The double-U grooves were filled with fairly small beads by making five passes on one side, back gouging the root and making all nine passes on the other side and then making the last four passes on the first side; the single-U grooves were filled in 23 passes. The small size of the individual beads resulted in a weld having good ductility, but because of the high welding speed used the total welding time was no more than would have been needed to fill the grooves by using fewer passes and producing larger weld beads.

The flow rate of the 75% argon, 25% helium gas was great enough (60 cfh) to ensure adequate shielding at all times; increasing the flow would not have been necessary had field erection been required.

Use of ⅛-in.-diam electrode wire, instead of the 3/32-in.-diam wire often used to weld 2-in. plate, reduced the number of passes that were needed by about one-half, and fully automatic welding permitted higher welding speeds. Use of automatic welding also ensured good control of weld quality. No peening or other in-process treatment was required during welding, and porosity was at an acceptable level. Welding conditions were the same for both types of joints and are given in the table that accompanies Fig. 13.

Welding With Large-Diameter Electrode Wires. The current density required for spray transfer with steady current is reduced for electrode sizes larger than standard. Current densities of 12,000 to 30,000 amp per square inch are used for welding with 5/32, 3/16, and 7/32-in.-diam electrode wires, compared with 30,000 to 100,000 amp per square inch for welding with 3/64 to ⅛-in.-diam wires. Using the larger-diameter wires, deposition rates of 15 lb per hour are readily obtained, compared with 5 to 10 lb per hour for standard sizes of wire, making this a method for low-cost welding of thick aluminum plate in the flat position. Most gas metal-arc equipment is designed for use with electrode wires not exceeding ⅛ in. in diameter, and this equipment may not be suitable for welding with large-diameter wires. However, suitable equipment can usually be made by converting submerged-arc equipment. Constant-current motor-generator power supplies are preferred, although rectifiers have been used.

When welding with large-diameter electrodes, somewhat different techniques are required to ensure 100% fusion to the sidewalls of grooves. In general, double-V grooves with fairly wide included angles (45° to 90°) are preferable to deep, narrow grooves. Shorter arc lengths, which give more fusion at the sidewalls, must be used. The arc should be shortened until the characteristic hissing disappears and is replaced by a popping sound. The welding speed should always be low enough to allow the arc to impinge on the molten puddle. Although 100% argon can be used for most applications, the addition of helium to the argon increases penetration. Conditions for welding butt joints in metal thicknesses from ¾ through 3 in. are given in Table 15; Table 16 summarizes conditions for welding corner joints with fillets sized from ½ through 1½ in. Every procedure listed in the tables has met the requirements of Section IX of the ASME Boiler and Pressure Vessel Code. Thick-wall spheres, large cranes and other massive structures have been welded by this method.

Weld Backing for Gas Metal-Arc Welding

Backing bars are commonly used for gas metal-arc welds in butt joints, as this permits welding to be accomplished at higher speed, with less operator skill and with less control of welding conditions, especially when using spray transfer for joining thin sections. Steel is the material most commonly used for temporary backing of welds in aluminum alloys. Carbon steel is often used, but stainless steel is used when lower thermal conductivity is required in the backing. Copper and aluminum may be used when higher thermal conductivity is needed. Backing made of magnetic material sometimes deflects the arc and interferes with welding. When this occurs, nonmagnetic materials such as austenitic stainless steel, copper and aluminum should be used instead.

Austenitic stainless steel backing bars have reasonable life against arc damage and do not produce arc blow; their use minimizes the possibility of iron or rust pickup in the root bead. When copper backing is used, copper pickup must be prevented. Local deposition of copper or copper-aluminum alloy can result in corrosion in service. Life of copper backing is somewhat less than that of stainless steel, especially under direct arc impingement. Chromium plating of copper backing has been used to reduce copper pickup and increase backing life. Aluminum backing with a hard anodic coating will provide adequate chilling; an added advantage is that the arc will not strike the aluminum backing and cause damage, because the anodic coating is an excellent dielectric.

Backing bars may be temporary, permanent, or integral. Temporary aluminum backing is removed by chipping after welding. It is not necessary that a butt weld be completely fused to the temporary aluminum backing, provided that the root pass is back gouged to sound metal after the backing bar has been removed. Temporary backing should be grooved to allow the root surface of the weld to protrude beyond the plane of the back surface of the workpiece, thereby ensuring adequate penetration. This groove should be shallow (0.010 to 0.030 in.) and wider than the width of the root surface of the weld. Too wide a groove will give insufficient support to the metal under the hold-down clamps.

Although the chilling effect of the backing bar may be advantageous at times, at other times it may be a disadvantage, and then it is common practice to place sheets of asbestos between the backing bar or clamps, and the work metal. The asbestos sheets should not be placed directly beneath the joint. Properly placed strips of asbestos will provide a backing groove and will eliminate the need for a groove in the backing bar.

Temporary backing bars may be seen with the butt welds in Fig. 6. Example 295 describes how backing inserts of different metals can be used to slow down or accelerate the cooling of a joint during welding.

When permanent aluminum backing is used, it is necessary to obtain complete fusion between the backing, the root faces and the root layer of the weld. This is facilitated by using a greater root opening than is employed with temporary backing. Mechanical and magnetic oscillation can be used to help achieve fusion to both root faces in a single pass. Permanent backing bars are shown with the five welds in Table 17. Service conditions do not always permit the use of permanent backing, but by eliminating the back gouging required when temporary backing is used, the use of permanent backing (when permitted) can reduce costs, as in the following example.

Example 297. Use of Permanent Backing Strips for Sounder Welds and Savings in Labor (Fig. 14)

Permanent backing strips were used in joining the starboard and port hull sections to the center hull section of an amphibious lighter made of 3⁄16-in.-thick alloy 5086 sheet. The strips, 1 in. wide by 3⁄16 in. thick, were tack welded to the inside seam edge of both the starboard and port hull sections while they were still in the subassembly fixture (Fig. 4c). The tack welds were 2 in. long on 6-in. centers. The starboard and port hull sections were then hoisted into the final assembly fixture (see Fig. 4d), and tack welded to the center section. Bulkheads and braces were welded in place and the bow was joined to the hull. Finally, the trunnions were fastened in place and the hull was turned over in the fixture

Table 15. Typical Butt Joints and Conditions for Gas Metal-Arc Welding With Large-Diameter Electrode Wires

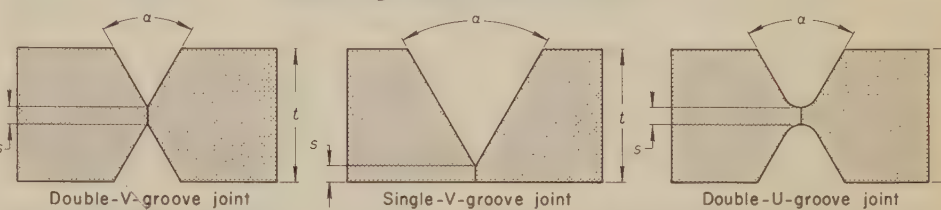
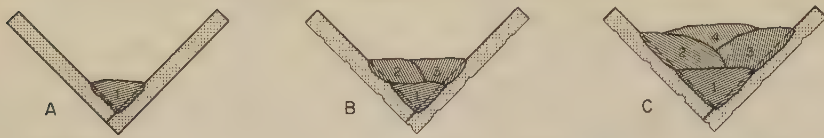


Plate thickness, t, in.	Joint design (see above): Groove type	Groove angle, α, deg	Root face, s, in.	Pass	Electrode-wire diameter, in.	Shielding gas	Gas flow, cfh	Arc current (dcrp), amp	Arc voltage(a), v	Welding speed, ipm
3⁄4	Double-V	90	1⁄4	1, 1st side	5⁄32	Argon	100	450	28	16
				2, 2nd side	5⁄32	Argon	100	500	28	16
3⁄4	Double-V	90	1⁄4	1, 1st side	3⁄16	Argon	100	450	32	15
				2, 2nd side	3⁄16	Argon	100	500	32	15
1	Double-V	70	3⁄16	1, 1st side	5⁄32	Argon	100	450	28	10
				2, 2nd side	5⁄32	Argon	100	500	28	10
1	Double-V	70	1⁄8	1, 1st side	3⁄16	Argon	100	500	26.5	12
				2, 2nd side	3⁄16	Argon	100	500	26.5	12
1 1⁄4	Double-V	70	3⁄16	1, 1st side	3⁄16	Argon	100	550	26.5	10
				2, 2nd side	3⁄16	Argon	100	550	26.5	10
1 1⁄4	Single-V	45	1⁄4	1, 1st side	5⁄32	Argon	100	500	25	10
				2, 1st side	5⁄32	Argon	100	500	27	10
				3, back	5⁄32	Argon	100	500	26	12
1 5⁄16	Double-V	70	1⁄4	1, 1st side	3⁄16	Argon	100	550	29	8
				2, 2nd side	3⁄16	Argon	100	575	29	8
1 1⁄2	Double-V	70	3⁄16	1, 1st side	7⁄32	Argon	100	650	27	8
				2, 2nd side	7⁄32	Argon	100	675	27.5	8
1 1⁄2	Double-V	70	3⁄16	1, 1st side	3⁄16	Argon	100	550	26	10
				2, 2nd side	3⁄16	Argon	100	575	27	10
				3, 1st side	3⁄16	Argon	100	600	29	10
				4, 2nd side	3⁄16	Argon	100	600	29	10
1 3⁄4	Double-V	70	3⁄16	1, 1st side	3⁄16	Argon	100	600	28	10
				2, 2nd side	3⁄16	Argon	100	600	28	10
				3 to 6, alternate	3⁄16	Argon	100	500	27	14
1 3⁄4	Double-V	70	1⁄8	1, 1st side	7⁄32	Argon	100	650	26	10
				2, 2nd side	7⁄32	Argon	100	650	26	10
				3, 1st side	7⁄32	Argon	100	600	27	10
				4, 2nd side	7⁄32	Argon	100	600	27	10
1 3⁄4	Single-V	45	1⁄4	1, 1st side	3⁄16	Argon	100	600	28	10
				2, 1st side	3⁄16	Argon	100	600	28	10
				3, 1st side	3⁄16	Argon	100	550	30	14
				4, 1st side	3⁄16	Argon	100	550	30	14
				5, back	3⁄16	Argon	100	550	30	10
2	Double-V	70	3⁄16	1, 1st side	3⁄16	75 He, 25 A	120	550	31	10
				2, 2nd side	3⁄16	75 He, 25 A	120	550	33	10
				3, 1st side	3⁄16	75 He, 25 A	120	550	32	10
				4, 2nd side	3⁄16	75 He, 25 A	120	550	33	10
2	Double-V	70	1⁄8	1, 1st side	7⁄32	Argon	100	600	26	10
				2, 2nd side	7⁄32	Argon	100	600	28	10
				3, 1st side	7⁄32	Argon	100	600	30	10
				4, 2nd side	7⁄32	Argon	100	600	30	10
2	Single-V	45	1⁄4	1, 1st side	3⁄16	Argon	100	600	28	10
				2, 1st side	3⁄16	Argon	100	600	28	10
				3 to 7, 1st side	3⁄16	Argon	100	500	26	14
				8, back	3⁄16	Argon	100	550	28	10
3	Double-V	70	1⁄4	1, 2 (b)	3⁄16	75 A, 25 He	100	600	25	9
				3, 4 (b)	3⁄16	75 A, 25 He	100	500	23	11
				5, 6 (b)	3⁄16	75 A, 25 He	100	625	26	9
				7 to 12 (b)	3⁄16	75 A, 25 He	100	600	27	9
3	Double-V	70	3⁄16	1, 2 (b)	7⁄32	75 A, 25 He	100	650	25	9
				3, 4 (b)	7⁄32	75 A, 25 He	100	500	23	10
				5, 6 (b)	7⁄32	75 A, 25 He	100	650	26	9
				7 to 10 (b)	7⁄32	75 A, 25 He	100	625	27	9
3	Double-U	30 (c)	1⁄2	1, 2 (b)	7⁄32	75 He, 25 A	120	650	29	10
				3 to 6 (b)	7⁄32	75 He, 25 A	120	650	31	10

(a) Voltages are measured from contact tube to test plate. Somewhat higher readings will result if drops in welding and ground leads are included. (b) The first side receives odd-number passes; the second side, even-number passes. (c) Radius of groove, 1⁄4 in.

Table 16. Typical Corner Joints and Conditions for Gas Metal-Arc Welding With Large-Diameter Electrode Wires (a)



Fillet size, in.	Pass type (see above)	Pass number	Electrode-wire diameter, in.	Arc current (dcrp), amp	Arc voltage(b), v	Welding speed, ipm
½	A	1	5/32	525	22	12
½	A	1	3/16	550	25	12
⅝	A	1	5/32	525	22	10
¾	A	1	5/32	600	25	10
¾	A	1	3/16	625	27	8
¾	A	1	7/32	625	22	8
1	B	1	5/32	600	25	12
		2, 3	5/32	555	24	10
1	B	1	3/16	625	27	8
		2, 3	3/16	550	28	12
1	A	1	7/32	675	23	6
1¼	B	1	5/32	600	25	10
		2, 3	5/32	600	25	10
1¼	B	1	3/16	625	27	8
		2, 3	3/16	600	28	10
1¼	B	1	7/32	625	22	8
		2, 3	7/32	625	22	10
1½	C	1	7/32	650	23	6
		2 to 4	7/32	650	23	10

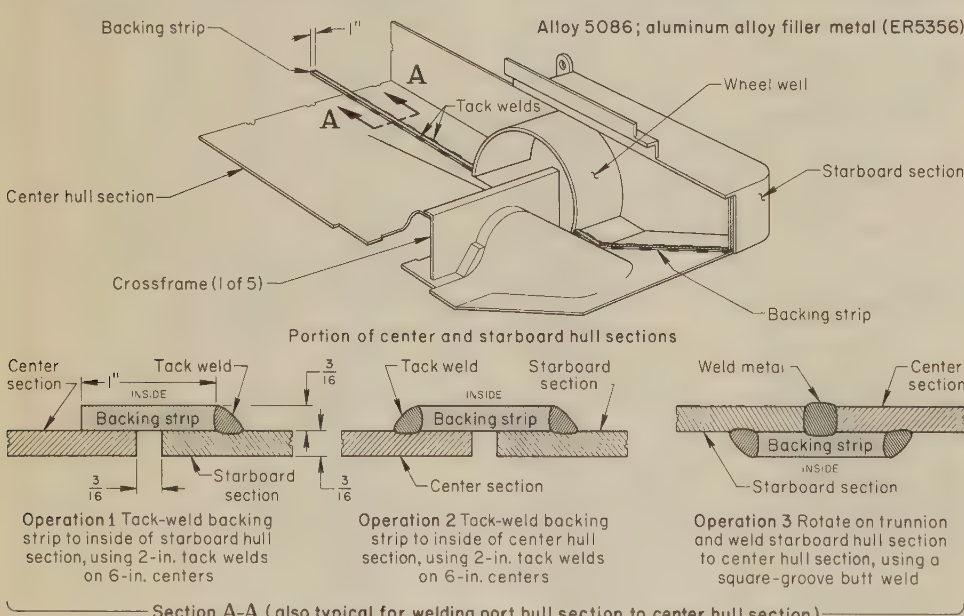
(a) Argon shielding gas, at 100 cu ft per hour. (b) Measured from contact tube to test plate.

to make the longitudinal weld on the outside. One welding pass was needed for one-third of the length and two passes for the other two-thirds. The placement of the backing strip and the welding sequence for attachment of the strip are shown in Fig. 14. The welding conditions are given in the table that accompanies Fig. 14.

The procedure originally used involved no backing strips. The first weld was made on the inside of the hull, the assembly was rotated, the root of the weld was back gouged by grinding, and two more passes were made on the outside of the joint.

The use of backing strips resulted in a saving of 8 hr of welding and back-gouging time at a cost of ½ hr to install the backing strips and an added material cost of $5.00. Because the welds using the improved method were subject to less rework based on the results of radiographic inspection, there was an added saving in reduced repair time. These improvements led to improved material flow, eliminated the need for one of the two trunnion fixtures, thus gaining 200 sq ft of floor space, and freed two machines for other welding.

Warpage was a serious imperfection, irrespective of the welding method and was never completely eliminated. Welding with a wandering sequence was helpful, but was at the discretion of the operator.



Conditions for Semiautomatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Square groove
Welding positions	Flat, vertical
Power supply	300-amp, constant-voltage transformer-rectifier
Fixtures	Assembly and clamping, mechanical shield jigs, permanent backing strip (see Fig. 4)
Precleaning	Wire brush, wipe with acetone
Electrode holder	Manual, water cooled
Electrode wire	3/64-in.-diam ER5356
Shielding gas	Argon, at 35 to 45 cfh
Current	220 to 250 amp, dcrp
Voltage	26 to 27 v
Welding speed	About 14 ipm
Number of passes	One, for flat position; two, for vertical position

Fig. 14. Section of amphibious lighter, showing use of backing strip for joining starboard and port sections to center hull section (Example 297)

Butt joints in extrusions can be designed so that the weld backing is an integral part of the extrusion. Integral backing is not recommended in environments where the nonwelded portion of the backing can promote crevice-type corrosion.

Multiple-Pass Gas Metal-Arc Welding

When welding joints in thin-wall vessels, it is sometimes desirable to use two passes rather than one, to avoid leakage due to porosity; gases can escape more easily from the smaller weld puddles, the second pass can fill some of the porosity that may exist in the first-pass weld bead, and there is little probability that any remaining pore in the first-pass bead will line up with a pore in the second-pass bead to produce a through hole.

For butt welding sections ⅜ in. thick or thicker, common practice is to weld from both sides when possible. Whether or not the first weld penetrates to the underside, the bead should be back gouged into sound fused weld metal before depositing the backing bead. Back gouging removes entrapped oxide film at the base of the weld bead. Proper depth is attained by gouging to the point where the chip no longer splits along the oxide film entrapped at the original face of the joint. Back gouging can be accomplished by a pneumatic hammer and knife-edge chisels of proper design, or by machining. Oil should not be used when back gouging, or it should be removed prior to welding. Disk grinders should not be used. Portable back-gouging equipment that employs shaped milling cutters is available. Regardless of method, the back-gouging groove should be of uniform shape, with no torn metal, sharp corners, or crevices from which oil or foreign material cannot be removed.

It is advisable to check that all defects extending to the gouged surface have been removed before depositing the backing bead. This check may be done by dye-penetrant inspection or, for the ultimate in weld quality, by radiographic inspection (as in Example 307) or ultrasonic inspection.

The shells of most aluminum vessels are thick enough to require at least two welding passes. In the feed-gas cooler shown in Fig. 15, 45 passes, made in the horizontal welding position, were required to complete the joining of a 3-in.-thick tube sheet to a 1½-in.-thick by 18-in.-OD pipe, both made from alloy 5083-O plate. In order to facilitate welding, the cooler was placed on turning rolls and rotated. Two welders worked simultaneously on the job; one at the 12 o'clock position and the other at the 6 o'clock position. The electrode holders were hand held, but were provided with supports to minimize operator fatigue. A constant-voltage power supply, a shielding-gas mixture of 75% argon and 25% helium, and ER5183 electrode wire were selected. A 1/16-in.-diam wire was used, allowing maneuverability of the electrode holder. None of the welded coolers failed the mass-spectrometer leak test.

Conditions for making multiple-pass welds in butt, corner and T-joints in ¼ and ⅜-in.-thick alloy 6061-T6 are given in Table 17. A multiple-pass technique was used in Example 298, for welding of pipe, and in Example 306, where leaktight joints were required.

Automatic Gas Metal-Arc Welding

When the size of the production run warrants the installation cost and setup time, the use of automatic gas metal-arc welding equipment offers several advantages, among which are better quality on a more consistent basis and higher welding speed than can be obtained with manual manipulation of the electrode holder. An application where the higher welding speed greatly reduced welding time is described in the following example.

Example 298. Use of Automatic Gas Metal-Arc Welding of Pipe To Greatly Reduce Welding Time (Fig. 16)

Joining lengths of alloy 6351-T4 pipe in the field by automatic gas metal-arc welding was found to be economical for lengths of five miles or more for a 6-in.-diam pipe (Fig. 16).

The U-groove joint with ends butted tightly, as shown in Fig. 16, was essential for the process. After cleaning the joint by wiping with solvent, alignment and backing for the root bead were accomplished by an internal tool that could be expanded and collapsed manually by means of an extension handle. Use of the alignment tool made tack welding unnecessary. The alignment tool was withdrawn as soon as the root bead was completed; it was used to align the next joint while welding of the previous joint was continued.

Welding was accomplished with an air-cooled electrode holder (with electrode-wire spool attached) mounted on a machine that rotated it around the pipe. In this way, a six-pass weld was finished without

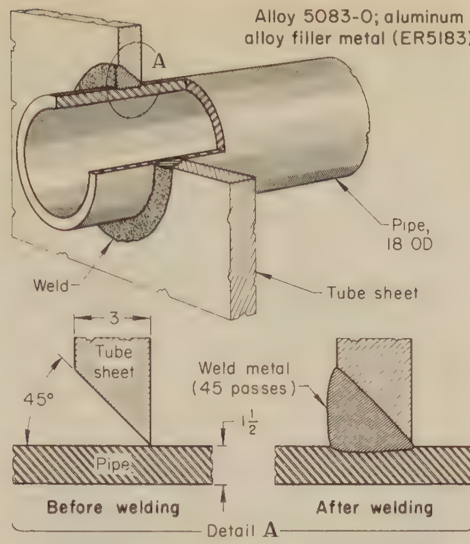


Fig. 15. Leak-free joint between tube sheet and pipe in an aluminum feed-gas cooler

stopping. Welding began near the top of the pipe and continued until the six passes were completed (Fig. 16). The electrode holder was adjusted for bead location and depth, and the direction of rotation was reversed after passes 2 and 5 without extinguishing the arc, to ensure adequate penetration and fusion, and correct weld-bead shape. Welding speed was fairly high (100 ipm), welding current was high (200 amp), and an electrode wire of small diameter (0.035 in.) was used. Welding conditions are given in the table with Fig. 16.

The estimated production rate, allowing for normal downtime, was 12 welds per hour per machine. The estimated production rate for welding with a manually manipulated electrode holder was five welds per hour per operator.

In the next example, the cost savings made possible by the higher welding speed helped overcome the high raw material cost of using aluminum rather than steel for the application.

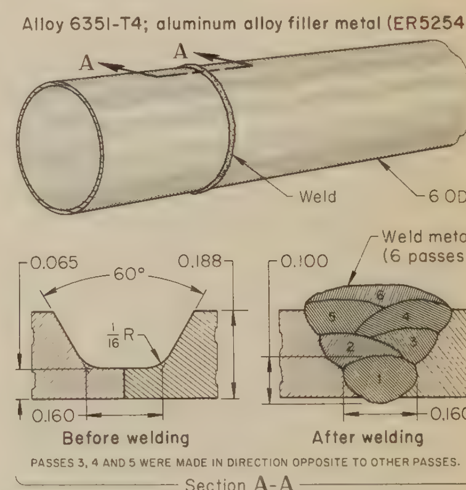
Example 299. Automatic Gas Metal-Arc Welding of Three Joints at a Time (Fig. 17)

By automatic gas metal-arc welding of three joints simultaneously, which reduced welding time to about one third of that for welding one joint at a time, aluminum alloy pressure cylinders of the type shown in Fig. 17 were made competitive with steel cylinders, despite the considerably higher cost of the aluminum alloys (5154-O, 6061-T1 and 6063-T42). Originally, a few aluminum alloy cylinders had been produced when the higher cost of aluminum was outweighed by its superior compatibility with the product being contained.

Designs for the various joints to be welded are shown in sections A-A, B-B, and C-C in Fig. 17. Before being assembled, the components were cleaned by (a) immersing them in a caustic etch-cleaner at 145 to 155 F for 4 to 6 min; (b) rinsing in warm water (100 to 120 F) for 1 min, in a bath that was overflowing and air agitated; (c) deoxidizing in an acid bath at 70 F minimum for 8 to 10 min; and (d) rinsing in warm water (125 to 145 F) for 1 min, in an overflowing bath.

The straight-side upper shell was pressed over the offset lower shell, this subassembly was placed in a welding lathe together with the collar and foot ring, and the parts were clamped by means of an air cylinder in the lathe tailstock. The assembly was rotated by means of a variable-speed drive.

Three electrode holders and wire drives were attached on side-beam carriages behind the lathe, which allowed for adjustment for cylinders of a variety of sizes. The welding controls included an adjustable weld timer to ensure correct overlap at the ends of the welds and provision for preflow and postflow of shielding gas. All of the controls were in one console.



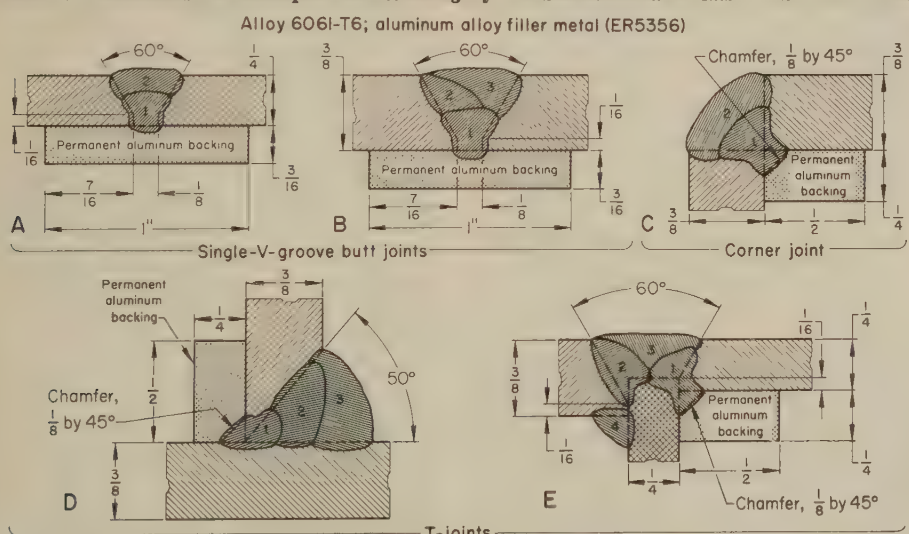
Automatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Single-U groove
Root opening	None
Welding position	Horizontal-fixed pipe
Power supply	300-amp engine-driven generator
Fixture	Expandable mandrel
Electrode holder	Mechanized, air cooled
Electrode wire	0.035-in.-diam ER5254(a)
Shielding gas	Argon, at 60 cfh
Current	200 amp, dcrp
Voltage	20 to 24 v
Welding speed	100 ipm
Arc time per joint	80 sec
Number of passes	Six
Production rate per machine	12 welds per hour

(a) Chosen because it is compatible with all common aluminum alloys used for pipe and pipe fittings, ER5254 is a former AWS classification that has been replaced by ER5654.

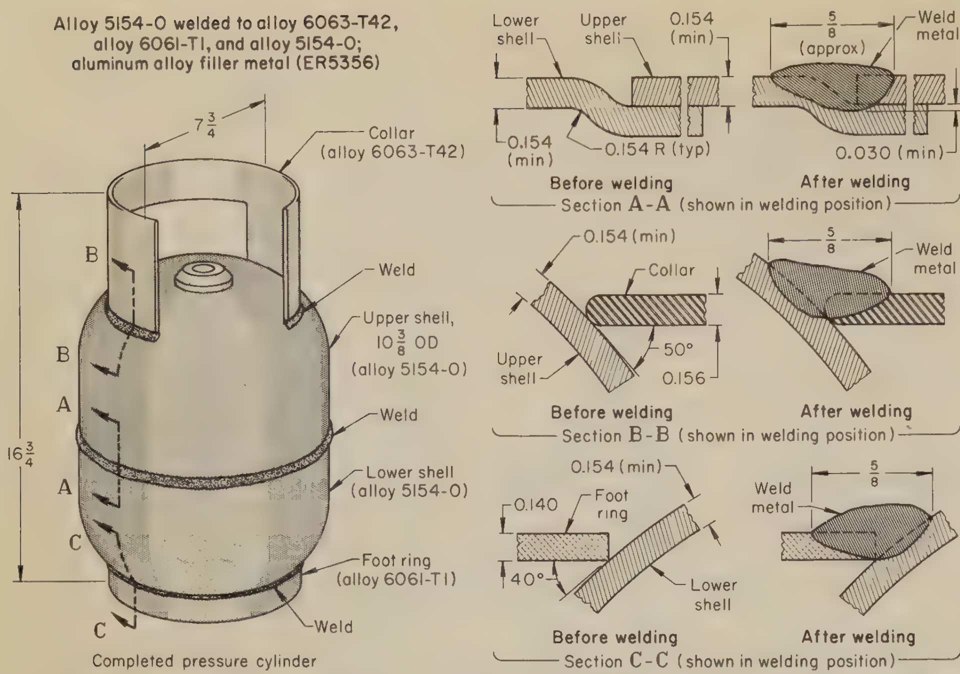
Fig. 16. Large pipe that was automatic gas metal-arc welded (Example 298)

Table 17. Conditions for Multiple-Pass Welding by the Semiautomatic Gas Metal-Arc Process



Base metal	Alloy 6061-T6
Electrode wire	3/64-in.-diam ER5356
Shielding gas	75% He, 25% A; 50 cfh
Welding positions	Flat and horizontal
Precleaning	Chemical
Interpass cleaning	None

Item	A	B	C	D	E
	Welding conditions for joints illustrated above				
Joint type	Butt	Butt	Corner	T	T
Current (dcrp), amp	180 to 200	180 to 200	180 to 200	190 to 220	180 to 210
Voltage, v	22 to 24	22 to 24	22 to 24	22 to 25	22 to 24
Welding speed, ipm	25 to 30	25 to 30	25 to 30	20 to 28	25 to 30
Number of passes	2	3	2	3	4



Conditions for Automatic Gas Metal-Arc Welding

Joint and weld types	See figure
Welding position	Horizontal-rolled pipe
Power supply	Three 500-amp transformer-rectifiers; adjustable slope and voltage control
Mechanization	Lathe with variable-speed drive, three electrode holders
Wire-feed system	Variable speed
Electrode holder	Mechanized, 700 amp, water cooled
Electrode wire	ER5356
Shielding gas	Argon, at 50 cfh
Number of passes	One

	Section A-A	Section B-B	Section C-C
Electrode-wire diam, in.	1/16	3/64	3/64
Current (dcrp), amp	290	200	190
Voltage, v	24	25	25
Wire-feed rate, ipm	240	325	310
Welding speed, ipm	45	34.7	42

Fig. 17. Pressure cylinder on which three welds were made simultaneously by automatic gas metal-arc welding (Example 299)

After alignment of electrode holders had been checked, all three welds were started simultaneously by pushing a master start button. Welding equipment and conditions are given in the table that accompanies Fig. 17. There was no postweld heat treatment, but all parts were postweld cleaned in hot dilute phosphoric acid.

All welds had to be free of undercutting on the sidewalls of the welding groove and the adjoining base metal, and it was specified that any crack, leak or other defect that appeared on the surface on a weld bead could be repaired only in accordance with a repair welding procedure for the weld in question.

Each cylinder was proof tested to 480 psig, and checked for leaks while under pressure. One cylinder from each lot of 200 cylinders or less was subjected to a series of tests. The first was a tension test across the girth weld (section A-A in Fig. 17), where minimum tensile strength required was 30,000 psi, and the minimum tensile strength calculated on the minimum wall thickness had to be at least the wall stress calculated for 960 psig. A weld-root bend test was also required. Two samples of the base metal were tension tested and both were required to meet the following requirements: tensile strength exceeding the wall stress calculated for 960 psig, yield strength not exceeding 80% of the tensile strength, and elongation in 2 in. of at least 7%. The chemical composition of the base metal was also verified.

One cylinder of each lot of 1000 cylinders was hydrostatically tested to destruction by bursting. Minimum pressure at failure was required to be 960 psig.

All pressure testing was conducted hydrostatically. Cylinders were filled with water and connected to an air-operated hydraulic pump. The low compressibility of water minimized the stored energy in the cylinder and the hazards that attended the bursting test.

Cylinders with valves, for liquefied petroleum gas service, were pressurized with 150 psig dry air after valves were attached. The entire assembly was submerged in a tank of water (with added wetting agent). Leaks showed as a stream of fine bubbles.

The production rate for automatically making three welds simultaneously was about the same as would have been expected for welding the girth joint alone, and there was no extra handling time.

In the example that follows, the reduced welding time and reduced distortion that resulted from the high welding speed obtained by automatic welding were important advantages.

Example 300. Reduction in Welding Time and Distortion by Changing From Semiautomatic to Automatic Gas Metal-Arc Welding (Fig. 18)

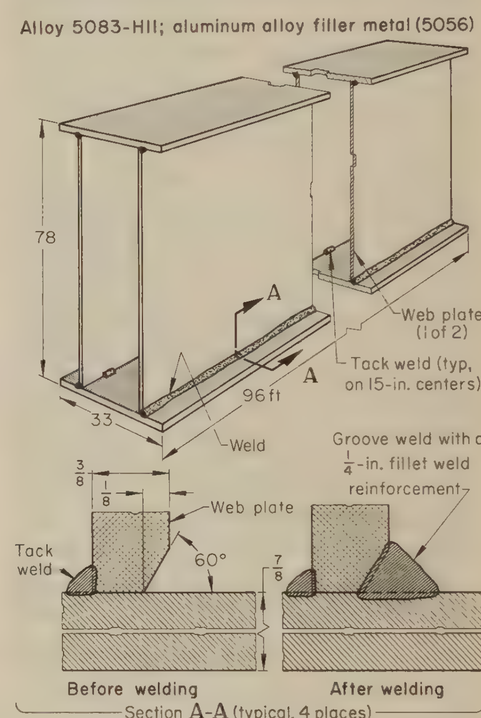
Originally, the four continuous welds along the full 96-ft length of the alloy 5083-H11 overhead-crane girder shown in Fig. 18 were made as fillet welds in square-groove joints by semiautomatic gas metal-arc welding. By changing to the single-bevel-groove weld with fillet weld reinforcement shown in section A-A in Fig. 18, and to fully automatic gas metal-arc welding, welding time was reduced by 80%. The 60° groove provided by beveling the web plates contributed to the reduction in welding time by allowing a 33% decrease in weld metal, at no sacrifice in joint strength. Welding current was increased from 260 to 375 amp.

The girders were tack welded at 15-in. centers on the inside to hold them in place for fillet welding. The continuous machine fillet welds were made in the horizontal position.

Other benefits of machine welding were a significant reduction in distortion, better joint appearance, and elimination of the defects associated with weld starts and stops. Welding conditions and a comparison of semiautomatic and automatic welding are given in the table with Fig. 18.

Production Examples of Gas Metal-Arc Welding

For the welding of aluminum, the gas metal-arc process affords welding speeds equal to or greater than those of other arc welding processes. This has led to other advantages, such as lower cost and less distortion. The previous section described some advantages of automatic gas metal-arc welding, most of which relate to the welding speed realized with this method.



Automatic Gas Metal-Arc Welding

Joint type	T
Weld type	Single-bevel-groove fillet
Root opening	None
Welding position	Horizontal
Power supply	500-amp, constant-current transformer-rectifier
Wire-feed system	Constant speed
Electrode holder	Mechanized, water cooled
Electrode wire	1/16-in.-diam alloy 5056(a)
Shielding gas	Argon, at 60 cfh
Current	See below
Voltage	26 v
Wire-feed rate	410 ipm
Welding speed	See below
Number of passes	One

Comparison of Semiautomatic and Automatic Gas Metal-Arc Welding

	Semi-automatic	Fully automatic
Current (dcrp), amp	260	375
Welding speed, ipm	12	20
Duty cycle per joint, %	33⅓	100
Welding time per joint, min	288	58
Shielding-gas consumption per joint, cu ft	64	60
Electrode consumption per joint, lb	12	8

(a) This electrode wire has been discontinued. See the footnote in the table that accompanies Fig. 22.

Fig. 18. Overhead-crane girder, the welding of which was changed from semiautomatic to automatic gas metal-arc to reduce welding time and distortion (Example 300)

Cost Savings. Higher welding speed usually results in a higher production rate per man-hour, and the lower labor cost per weld significantly affects the cost of a fabricated part. In the example that follows, a continuous-bead weld produced by gas metal-arc welding replaced a joint made by resistance spot welding and brazing, at a cost saving and with an improvement in the quality of the product.

Example 301. Gas Metal-Arc Welding of a Dust-Tight Box Cover at 60% Lower Labor Cost (Fig. 19)

When the joining process was changed from resistance spot welding plus torch brazing to continuous-bead semiautomatic gas metal-arc welding, the alloy 6061-T6 box cover shown at top left in Fig. 19 was produced not only to required dust-tightness (not attainable by spot welding plus brazing), but also at a 60% cost saving. The resistance spot welds had been placed on 1-in. centers, which permitted dust to penetrate between them during service. Torch brazing had been used at the corner gaps.

The fixture used for gas metal-arc welding was an angle-iron table with side-edge and front-edge stops, as shown in the upper right-hand corner of Fig. 19. With the parts in the position shown in the two middle views in Fig. 19, each of the ends was tacked to the cover at four places with fillet welds (lap joints), and the butt joints at the four mitered corners of the flange were tacked with square-groove welds. The square-groove tack welds, which extended to within 1⁄16 in. of the edge of the flange, were made with a minimum of weld-metal buildup. A copper bar served as a positioner and heat sink for the square-groove tack welds.

After the cover had been tack welded, it was turned over (see upper right-hand view in Fig. 19). Gaps between the ends and the cover were hammer closed and tack welded where needed. A copper backing vise gripped the back edge of the cover, a copper spatter shield was placed over the end, and the joint was welded from the apex of the cover to the back edge. The workpiece was reclamped and the joint from the apex to the front edge was welded. The second end was welded on in the same manner. A contoured arm rest assisted in electrode-holder guidance. After welding, the weld surfaces were wiped clean with a cloth and rough spots on the weld were hammered smooth. Welding conditions are given in the table with Fig. 19.

The following example describes an application in which the replacement of riveting by gas metal-arc welding resulted in a cost saving and an improvement in the product.

Example 302. Reduction in Cost and Rejection Rate by the Use of Gas Metal-Arc Welding Instead of Riveting (Fig. 20)

The truck-radiator grill frame shown in Fig. 20, an assembly of alloys 5052 and 6063 components, was originally joined by riveting with a hand-operated air gun, using rivet sets and a bucking bar. Cutouts were needed in the clamping fixture around each rivet, to allow use of the gun and bucking bar. These cutouts weakened the fixture, and the assemblies became twisted, resulting in a 12% rejection rate. Some assemblies also were out-of-square, as the joints could not be held tight and flush before riveting.

By changing from riveting to gas metal-arc welding, it was possible to use clamps that held the assemblies more securely in position during joining. Completed assemblies had more accurate dimensions and improved rigidity. Other advantages were a reduction of rejects to 1% and a 50% saving in labor time.

The assemblies were manually loaded in the welding fixture, toggle-clamped, welded in a single pass (with ER4043 filler metal, for maximum ease of welding and corrosion resistance), unclamped, and then manually unloaded. The weld passes were horizontal and vertical-up. Intermittent welding was used for all joints over 1 in. long, the procedure being to weld 1 in. and skip 4 in. Conditions for semiautomatic gas metal-arc welding are given in the table that accompanies Fig. 20.

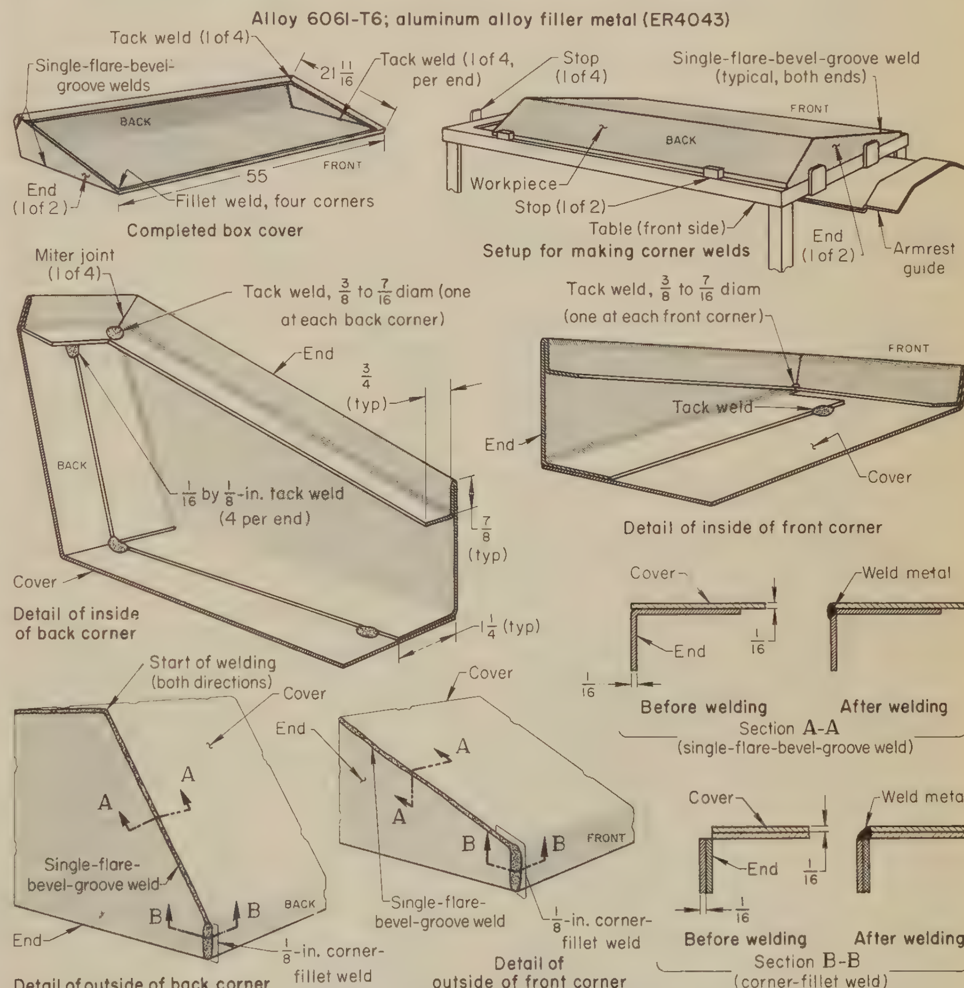
All welds had good penetration, and weld buildup was kept to a minimum. Typical penetration was 30 to 50% of the 3⁄16-in. lower channel thickness and 40 to 60% of the 1⁄8-in. thickness of the other parts.

Minimizing Distortion. High welding speed results in less heat being absorbed by the metal being welded, which in turn results in less thermal expansion, less residual stress and less distortion. In the following example, when resistance spot welding proved unsuitable because of the inaccessibility of joints, gas metal-arc welding was selected because it caused less distortion than the other arc welding processes, although more than resistance spot welding. Close dimensional control was achieved with proper fixturing.

Example 303. Use of Gas Metal-Arc Welding in the Final Assembly of a Frame for a Truck Cab Door (Fig. 21)

Both gas metal-arc welding and resistance spot welding were used in making the alloy 6061 military-truck-cab doorframe shown in Fig. 21. The resistance spot welding is described in Example 419, in the article on Resistance Welding of Aluminum Alloys. Because some of the doorframe joints were inaccessible for resistance spot welding, or had limited accessibility (see detail A, Fig. 21), gas metal-arc welding was selected as the best alternative — its high welding speed caused less distortion than the lower welding speed of gas tungsten-arc welding. However, it was advisable to hold the gas metal-arc welds to a minimum for two reasons: (*a*) Because the heat input was greater than in resistance spot welding, the probability of distortion in the highly stressed, tempered and cold worked material was greater; and (*b*) the larger mass of the weld metal produced greater residual stress during contraction in cooling.

An important requirement of the military truck was that it be able to float

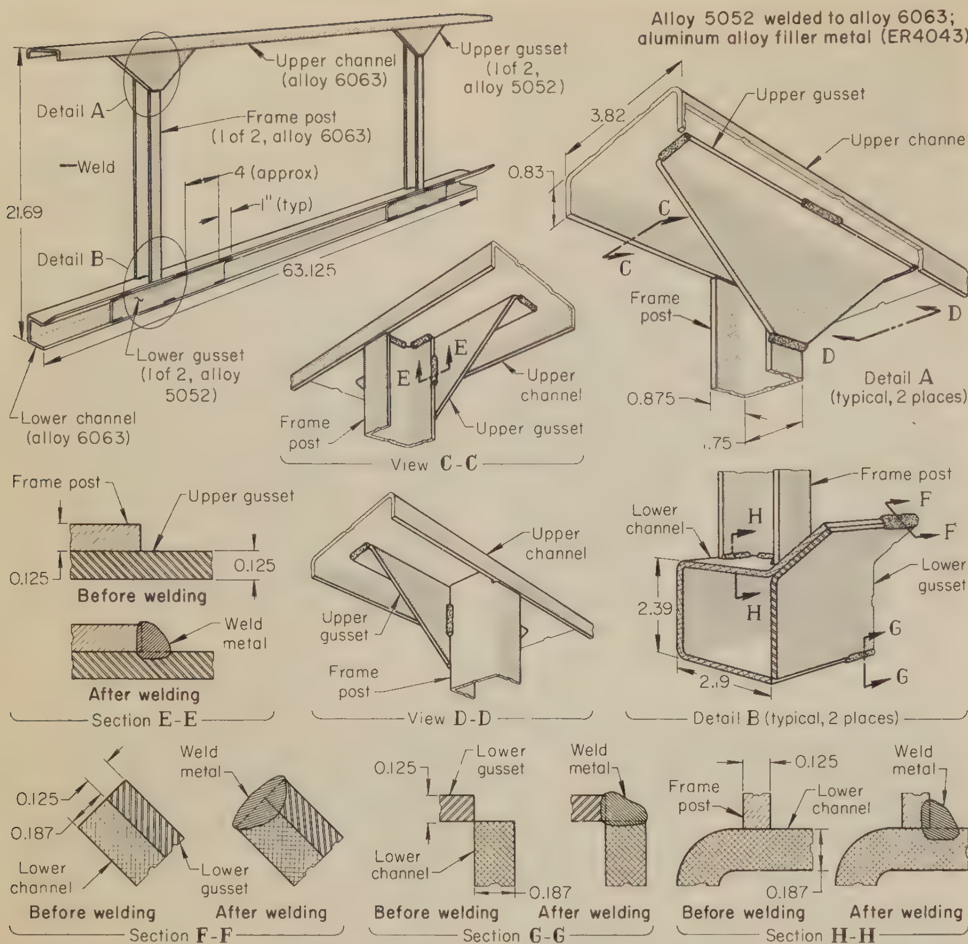


Conditions for Semiautomatic Gas Metal-Arc Welding

Joint types	Butt, lap, corner	Fixtures	Clamping, copper backing bar, copper spatter shield
Weld types	Square groove, fillet, single-flare-bevel groove	Electrode holder	Air cooled
Welding positions	Flat, vertical	Electrode wire	0.030-in.-diam ER4043
Power supply	500-amp, constant-voltage transformer-rectifier	Shielding gas	Argon, at 30 cfh
Wire-feed system	Variable speed(a), automatic current-voltage control	Current	90 to 100 amp, dcrp
		Voltage	17 to 18 v
		Number of passes	One

(a) Wire was fed from a 1-lb spool that was mounted on the electrode holder.

Fig. 19. Box cover that was gas metal-arc welded to ensure dust-tightness (Example 301)



Conditions for Semiautomatic Gas Metal-Arc Welding

Joint types	Corner, T, lap, edge	Shielding gas	Argon, at 35 cfh
Weld types	Square groove, fillet	Number of passes	One
Welding positions	Horizontal, vertical up	Current	115 amp, dcrp
Power supply	300-amp three-phase rectifier	Voltage	20 v
Wire-feed system	Electric push – air pull	Wire-feed rate	450 ipm
Electrode wire	0.035-in.-diam ER4043	Welding speed	24 ipm

Fig. 20. Truck-radiator grill frame that was gas metal-arc welded at an improvement in quality and reduction in costs over riveted assembly (Example 302)

(swim) when fully loaded, the tractor portion being given buoyancy by a watertight cab. In order that the doors be watertight, the frames had to be built to close dimensional tolerances, so that they would fit snugly in their openings. Both fixturing and welding were critical in maintaining dimensions.

Gas metal-arc welding was done without removing the frame from the same rigid fixture (see Fig. 21) used for resistance spot welding. Welding conditions are given in the table that accompanies Fig. 21. After welding, the frame was allowed to cool and was removed from the fixture to check dimensions and shape. The weldment was then furnace heated at 380 F for 6 hr to T6 condition, and tested for hardness. One frame per week of production (400 doors) was strength tested to destruction.

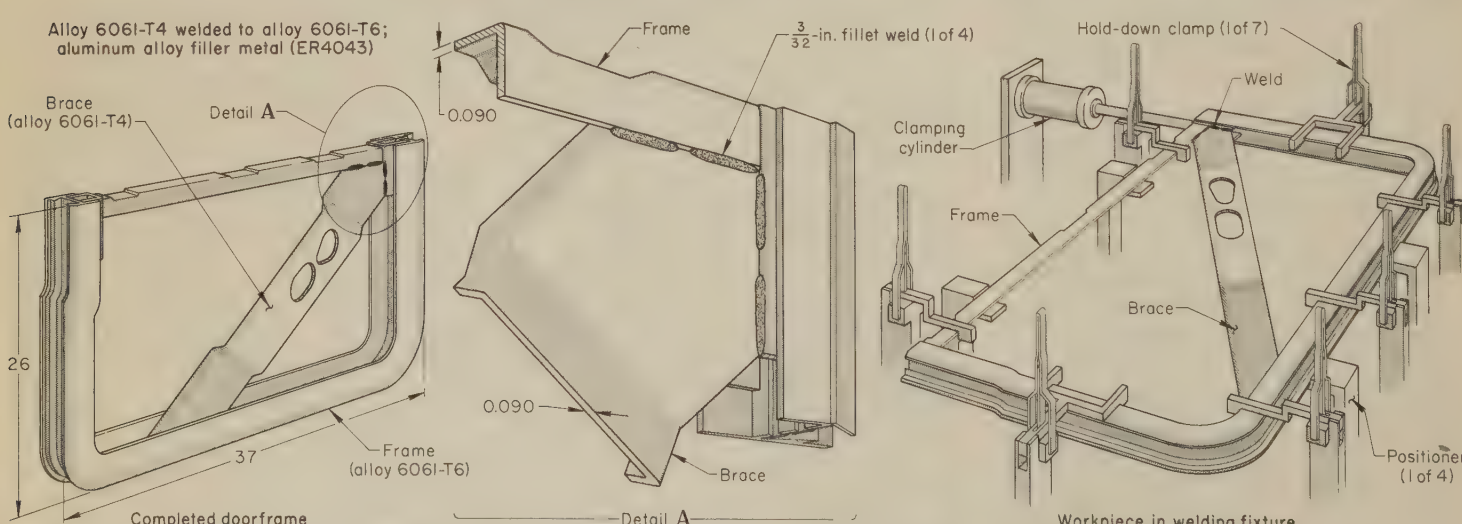
Final checking of dimensions and shape of each frame occurred after it was incorporated in a completed door assembly, and the latter had been installed in a truck cab. The cabs were then tested for watertightness by immersing them in water to within 4 in. of the freeboard of the truck. The first cab of a production lot was permitted a door fit that leaked one quart in 6 hr. All other cabs of the lot were required to show no visible leakage after 2 min of immersion.

Often, the welding sequence may be arranged so that only a minimum amount of fixturing is needed. This is illustrated in the following example.

Example 304. Welding Alloy 5083-H11 Plate by the Semiautomatic Gas Metal-Arc Process (Fig. 22)

Transverse joints in ⅞-in.-thick alloy 5083-H11 flange plates for overhead-crane girders were welded in ten passes by the gas metal-arc process. Although welding time could have been reduced by using a fully automatic procedure, the amount of welding did not justify the cost of obtaining and setting up the necessary equipment, so semiautomatic welding was used.

The edges of the plates were prepared as shown in Fig. 22. The joints were then tack welded, starting and runoff tabs were attached, and welding was begun. After the third pass, the plates were turned over, the joint was back gouged to remove root defects, and three weld passes were made on this side of the joint. In order to check



Conditions for Semiautomatic Gas Metal-Arc Welding

Joint type	Lap	Wire-feed system	Variable speed(a)	Current	110 amp, dcrp
Weld type	Fillet	Fixtures	Clamps	Voltage	19 v
Welding position	Horizontal	Electrode holder	100 amp, air cooled	Wire-feed rate	180 ipm
Power supply	200-amp, constant-voltage transformer-rectifier	Electrode wire	0.030-in.-diam ER4043	Welding speed	12 ipm
		Shielding gas	Argon, at 30 cfh	Number of passes	One

(a) Wire was fed from a 1-lb spool that was mounted on the electrode holder.

Fig. 21. Truck-cab doorframe on which the gas metal-arc process was used to make the fillet welds shown (Example 303)

distortion, the plate was turned over three times during welding. The last two passes on each side were made with a longer arc, in order to obtain the required weld contour. About 1¾ lb of electrode wire was used for each 33-in.-long weld. Further welding details are given in the table that accompanies Fig. 22.

Gas metal-arc welding is often used for making tack welds when final welding is to be done by the gas tungsten-arc process, as in the following example.

Example 305. Use of the Semiautomatic Gas Metal-Arc Process for Tack Welding Aluminum Fuel-Tank Assemblies (Table 18)

For tack welding the 50 subassemblies and the final assembly of a fuel-storage tank for an M-60 combat tank, gas metal-arc welding was selected in preference to gas tungsten-arc welding, for these reasons: (*a*) the higher welding speed of the gas metal-arc process resulted in less distortion; (*b*) the faster welding reduced welding cost; (*c*) the electrode holder was easier to manipulate in the various welding positions; (*d*) the penetration obtained in the ⅛-in.-thick metal was excellent; (*e*) the cleaning action of the reverse-polarity direct current ensured oxide-free welds.

The parts were clamped in fixtures and tacked with 1-in.-long welds on approximately 4-in. centers, using the equipment and settings listed in Table 18. To keep distortion to a minimum, tack welding sequences for each subassembly were developed. Because of the variety of shapes, these sequences were arrived at by trial-and-error, but in general they were based on working outward from the center of joints and assemblies.

To facilitate manipulation of the electrode holder, the electrode wire was fed from a 1-lb spool mounted on the holder. Quality control of the electrode wire was necessary. In addition to the requirement that the wire meet military specification MIL-E-16053, samples of wire were tested periodically for cleanness, as described in Example 311. The wire was ordered in a very hard (H19) temper so that the small knurled drive wheels used in the wire feed would not allow the wire to slip. When softer wire was used, the knurled drive wheels would sometimes "mill" the wire, which caused it to slip and produce a burnback.

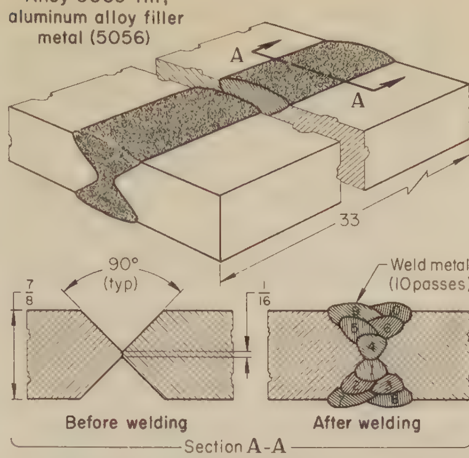
Example 293 describes preweld cleaning of the alloy 5083-H112, alloy 5086-H32, and alloy 6061-T6 components of the subassemblies, and Example 311, final seam welding.

Soundness of Welds Made by Gas Metal-Arc Welding

The five principal defects encountered in gas metal-arc welding of aluminum alloys are transverse weld-metal cracking, longitudinal weld-metal cracking, crater cracking, porosity, and inadequate penetration. In addition, inclusions and cold laps are occasionally encountered.

Transverse and longitudinal weld-metal cracking are usually associated with the higher-strength aluminum alloys of the 2*xxx* and 7*xxx* series. In particular, cracks are likely to originate at the starting and stopping points of the arc, because craters caused by normal shrinkage occur in these areas. Therefore, it is good practice to use starting and runoff tabs and not to start or break the arc on the workpiece.

In one application, consistency of weld quality in ¾-in. alloy 2219-T87 plate was improved by replacing a double-V-groove weld that required eight passes (four from each side) with a double-U-groove weld that required only three passes. First, the ⅛-in. root face of the double-U groove was welded, and then a facing pass was made on each side of the groove with the electrode holder oscillating from side to side to fill the remainder of the groove completely. (Mechanical and magnetic equipment is available to produce an oscillation in which both frequency and amplitude are adjustable.) The weld was used to join two barrel sections to form a space-launch booster tank. Welding position was vertical.



Semiautomatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Double-V groove
Welding position	Flat
Power supply	500-amp, constant-current transformer-rectifier
Wire-feed system	Constant speed
Electrode holder	Water cooled
Electrode wire	1/16-in.-diam alloy 5056(a)
Shielding gas	Argon, at 40 cfh
Current	260 to 270 amp, dcrp
Voltage	25 v
Welding speed	16 to 25 ipm
Number of passes	Ten
Total welding time per joint (33⅓% duty cycle)	45 min

(a) Alloy 5056 electrode wire has been discontinued and has been replaced by ER5356, which has the same chemical composition except for lower limits on silicon and iron and the addition of a small amount of titanium. The titanium addition refines the grains and reduces tendency for hot-short cracking. For general-purpose welding, ER5183 (which gives greater ductility) is often used. For higher-strength welds, ER5556 is used. All three electrode types can be used with the welding conditions listed above.

Fig. 22. Double-V-groove weld in an alloy 5083-H11 flange plate for an overhead-crane girder (Example 304)

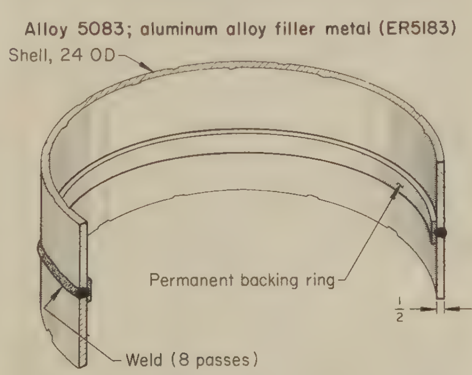


Fig. 23. Subcooler shell in which porosity was eliminated by increasing the arc voltage to produce a stiffer arc column in gas metal-arc welding

Table 18. Materials, Equipment and Operating Conditions for Tack Welding Fuel-Tank Subassemblies and Assemblies (Example 305)

(See Example 293 for a description of preweld cleaning and Fig. 36 for a view of the tank and some specific joints.)

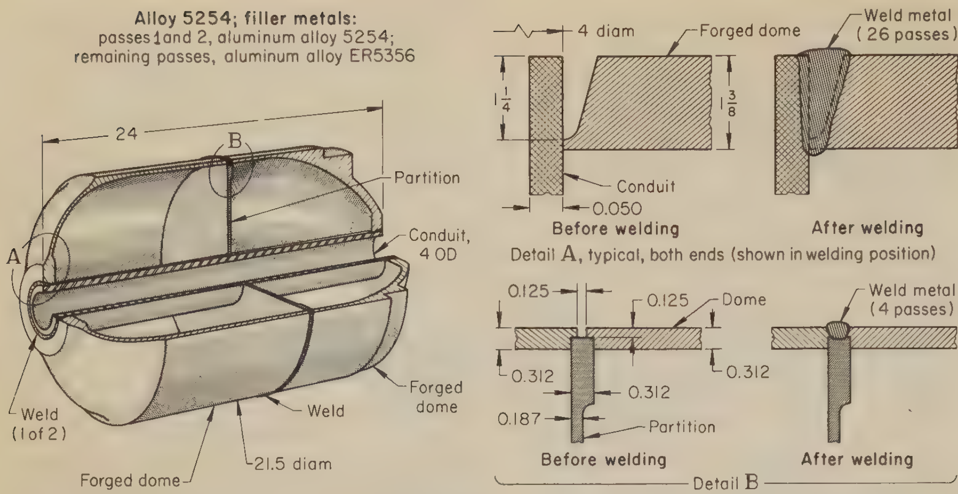
Base metals	⅛-in.-thick alloy 5086-H32 sheet, alloy 5083-H112 extrusions, alloy 6061-T6 fittings
Welding process	Semiautomatic gas metal-arc
Equipment	
Power supply	200-amp transformer-rectifier, 60% duty cycle
Electrode holder	200 amp, air cooled
Electrode wire	3/64-in.-diam ER5356
Shielding gas	Argon, at 30 to 40 cfh
Gas nozzle	⅝-in. diam
Fixtures	Clamps
Welding Conditions	
Joint types	Butt, lap, T, corner
Weld types	Square-groove, V-groove, fillet
Welding positions	Flat, vertical, horizontal
Current	160 to 180 amp, dcrp
Voltage	18 to 22 v
Wire feed	280 to 320 ipm
Number of passes	One

Weld-cracking problems can often be attributed to restrained shrinkage of the weld metal. Process variables that produce coarse-grain weld-metal deposits and large heat-affected zones are additional causes. For example, longitudinal weld-metal cracking in a square-groove butt joint in ⅛-in. alloy 5083 sheet was eliminated in one application by sufficiently relieving hold-down clamp pressure to allow slight transverse movement of the workpieces during welding. In addition, weld reinforcement was increased by reducing the welding speed, thereby creating a larger weld cross section that withstood the higher shrinkage stresses without cracking.

In another application, transverse weld-metal cracking in a square-groove butt joint in 3/16-in. alloy 5083 sheet was eliminated by increasing the solidification rate of the weld puddle. This was accomplished by reducing the arc voltage from 28 to 24 volts and the welding current from 280 to 185 amp, and increasing the welding speed from 18-to-25 to 27-to-30 in. per minute. The lower arc voltage resulted in a narrow, deeply penetrating weld and allowed the welding speed to be increased. In addition, the power supply was changed from the constant-voltage type to the conventional drooping-voltage type. The electrode diameter remained at 1/16 in. and the number of passes at two.

Sound, porosity-free welds meeting radiographic and mass-spectrometer leak-test requirements can be made in aluminum alloys by the gas metal-arc process, but careful attention must be given to the selection and use of welding equipment, materials, conditions and techniques.

Hydrogen contamination is the cause of virtually all weld porosity in aluminum alloys. Solidification shrinkage is of minor significance as a contributor to weld porosity. Hydrogen has high solubility in molten aluminum but very low solubility in solid aluminum (a small fraction of the solubility in solid



Item	Circumferential joint	Conduit-to-boss joint
Conditions for Automatic Gas Metal-Arc Welding		
Joint type	T	Corner
Weld type	See detail B	Single-J groove
Position	Flat	Flat
Power supply	500-amp, constant-voltage transformer-rectifier	500-amp, constant-voltage transformer-rectifier
Fixtures	Clamping jig, rotating positioner	Clamping jig, rotating positioner
Electrode holder	Water cooled	Water cooled
Gas-nozzle diameter	¾ in., all passes	Passes 1 to 4: ⅝ in.; passes 5 to 26: ¾ in.
Electrode wire(a)	Passes 1 and 2: 1⁄16-in.-diam 5254; Passes 3 and 4: 1⁄16-in.-diam ER5356	Passes 1 and 2: 1⁄16-in.-diam 5254; Passes 3 to 26: 1⁄16-in.-diam ER5356
Shielding gas	75% helium, 25% argon, at 30 cfh	75% helium, 25% argon, at 30 cfh
Current	1st pass: 180 to 190 amp, dcrp; Passes 2 to 4: 190 to 200 amp, dcrp	200 to 210 amp, dcrp (all passes)
Voltage	27 to 27½ v, all passes	27 to 27½ v, all passes
Welding speed	29 ipm	29 ipm
Number of passes	4	26 (approx)

(a) Electrode wires conformed to military specification MIL-E-16053. The 5254 electrode wires (no longer an AWS classification; replaced with ER5654) were selected for strength, and the ER5356 electrode wires, for better corrosion resistance.

Fig. 24. Pressure vessel that formed part of the fuel system of a naval torpedo, showing details of two principal joints (Example 306)

steel and titanium). Hydrogen dissolved in the molten weld puddle during welding is released during solidification. The high freezing rate associated with gas metal-arc welding can prevent the evolved hydrogen from rising to the surface of the weld puddle, with the result that porosity occurs. An extremely small amount of hydrogen source can cause significant amounts of porosity.

The major sources of hydrogen are hydrated oxide, oil and other hydrocarbon contaminants on the surface of the electrode wire. Other sources are moisture, oil, grease and hydrated oxide on the work-metal surface and moisture in the shielding gas. Factors that can contribute to porosity from contamination are insufficient gas flow, excessive distance from the gas nozzle to the work metal, leakage in the shielding-gas hose or fittings, and erratic electrode-wire feed.

When weld porosity is encountered, the electrode wire should be checked, first to determine whether it is clean, and then to determine whether it is capable of depositing sound metal. In some instances, a radiograph of a weldment made in the overhead position with the wire in question can be obtained from the producer of the wire. Also, a check weld (butt or fillet) can be made, broken open and examined. If the wire will produce sound welds on one machine but not another, the source of the porosity is elsewhere than the wire. One way to make sure the wire is not a source of hydrogen is to use shaved wire.

Next, conditions for gas metal-arc welding that will bring about a slower solidification rate should be selected. Welding in the flat or vertical position also aids escape of gases.

Correct voltage and arc length can reduce porosity in a weld, such as the one in the subcooler shown in Fig. 23. This vessel was fabricated from ½-in.-thick alloy 5083 by gas metal-arc welding in the vertical-pipe position. A constant-voltage power supply and 1⁄16-in.-diam ER5183 electrode wire were used with a welding current of 280 to 290 amp, a welding speed of 18 to 20 in. per minute, and 75% argon, 25% helium shielding gas. Eight passes were required. Severe porosity was encountered. After a thorough re-evaluation of the procedure, it was concluded that welding position had little effect on the porosity but that raising the arc voltage from the 24-to-26-volt range to the 28-to-29-volt range brought about a stiffer type of spray transfer that resulted in a dense, sound weld.

Another factor that contributes to gross porosity is incorrect or erratic wire feed, which results in an unstable arc. In general, the arc should be manipulated in a reciprocating fashion to obtain the maximum amount of stirring action in the weld puddle and so to assist gases to escape. Porosity can also be reduced by using a shielding-gas mixture containing a large proportion of helium.

A small amount of porosity scattered uniformly throughout a weld has little effect on the strength of the welded joint. Clusters of porosity and gross porosity can adversely affect weld strength. Various welding codes limit the amount and distribution of acceptable porosity.

Multiple-pass welding helps prevent leakage due to porosity, as explained in the section of this article on Multiple-Pass Gas Metal-Arc Welding. In the following example, leaktight welds were obtained in joints designed so that complete penetration was obtained; four passes were used for one type of joint and about 26 passes for the other type. (Leak-free joints can also be made in one pass, as described in Example 299.)

Example 306. Producing Leaktight Welds in a Pressure Vessel (Fig. 24)

The major components of the pressure vessel shown in Fig. 24 were two closed-die-forged domes, a central partition, and an axial conduit — all made of alloy 5254. The domes were joined by a single circumferential weld that also incorporated the partition as backing (Fig. 24, detail B). The conduit was welded to the vessel at both ends. Internal baffles and fittings (not shown in Fig. 24) completed the vessel structure, which later was shrink fitted into the 4340 steel shell of a naval torpedo, the vessel forming part of the fuel system. Joint designs and welds used to join the major components of the pressure vessel are shown in Fig. 24, details A and B. The principal conditions for automatic gas metal-arc welding of both joints are given in the table that accompanies Fig. 24.

The centrally located partition and the two dome sections were welded simultaneously (Fig. 24, detail B), in four passes. To ensure weld soundness, joints between the conduit and the 1⅜-in.-thick bosses were designed for full-penetration single-J-groove welds, and were completed in about 26 passes. These joints were economical to make and had a high degree of reproducibility. The welds were of excellent quality, showing "water clear" on x-ray plates.

After edge preparation (machining) and cleaning of joint areas, internal baffles and fittings (not shown in Fig. 24) were installed in the dome sections. These sections, together with the center partition, were then assembled in an alignment fixture, clamped, mounted (axis horizontal) under a fixed electrode holder and welded. The welding area was carefully shielded from drafts. During welding, the workpiece was rotated without stopping, except to change electrode wire, and the welds were wire brushed during rotation. The conduit was then inserted and similarly welded, with the axis of the assembly vertical. After welding, the vessel and welds were machined. Welds were inspected by liquid-penetrant methods and the vessel was subjected to a mass-spectrometer leak-rate test.

Mechanical problems, such as burnback of the electrode wire into the contact tube, snagging of the electrode wire either on the wire spool or in the flexible cable joining the spool to the electrode holder, and inability of the wire to maintain a constant arc length during welding (hunting), also occur. These are almost always associated with malfunctions of equipment (especially, wire-feeding equipment), rather than with process or material limitations. All of these difficulties with gas metal-arc welding, and several others, are listed in Table 19, along with their usual causes.

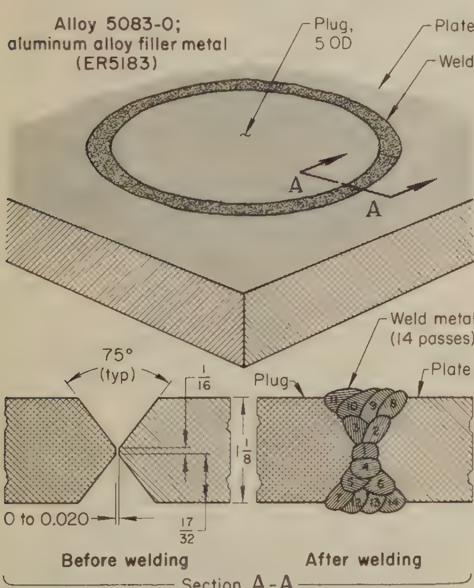
Repair Welding by the Gas Metal-Arc Process

Welding is widely used for repairing defects in both cast and wrought parts. The techniques for making such repairs vary, depending on the type of defect and the properties and condition of the part to be repaired. One repair technique used on plate is described in the example that follows.

Example 307. Repair Welding Alloy 5083-O Plate (Fig. 25)

A welding technique for repairing cracks (resulting from forming) in 1⅛-in.-thick alloy 5083-O plate included trepanning a circular plug, containing the cracks, from the plate and then welding in a plug of sound metal. The plug of sound metal was machined to fit the 5-in.-diam trepanned hole with a maximum radial clearance of 0.020 in., as shown in Fig. 25. The plug was inserted in the hole and held in place by three 2-in.-long tack welds spaced 120° apart. Next, the joint region was preheated locally to 200 F with an oxyacetylene flame and the first pass was made on the side opposite the tack welds, special care being taken to avoid melt-through. Passes 2 and 3 (Fig. 25) were then made, the tack welds were ground out, and the weld was inspected radiographically. The root pass was back gouged to a depth of about 3/32 in. and the next four passes were made. The remaining passes were deposited as shown in the welding-pass sequence in Fig. 25.

Each of the 14 welding passes was made in two parts, each part through approximately 180° of the joint. Upon completion of each part of a pass, the arc was diverted to a runoff tab and broken there instead of in the repair weld to avoid the possible formation of crater cracks in the



Semiautomatic Gas Metal-Arc Welding

Joint type	Butt
Weld type	Double-V groove
Welding position	Flat
Power supply	500 amp, constant voltage
Electrode wire	1/16-in.-diam ER5183
Shielding gas	75% helium, 25% argon, at 100 cfh, plus 99% argon, 1% oxygen, at 10 cfh
Current	300 amp, dcrp
Voltage	32 v
Preheat	200 F
Interpass temperature	150 to 200 F
Number of passes	14
Welding time	Approx 1½ min per pass

Fig. 25. Plate in which a crack was repaired by removing the cracked area by trepanning and then welding a sound plug in the hole (Example 307)

Table 19. Common Problems With Gas Metal-Arc Welding and Their Usual Causes

Porosity

1 Gas entrapment from poor shielding, shielding gas, air
2 Hydrogen from moisture, unclean wire surface, oil on base metal
3 Excessive cooling rate of weld puddle
4 Erratic electrode-wire feed (see causes in item 2 under "Arc-Length Fluctuations")
5 Erratic arc transfer, caused by incorrect current

Transverse Weld-Metal Cracking

1 Excessive longitudinal restraint
2 Slow solidification of weld puddle
3 Absorption of halogen compound in weld puddle
4 Incorrect combination of base metal and filler metal

Longitudinal Weld-Metal Cracking

1 Excessive transverse restraint
2 Concave, instead of convex, root-pass weld bead
3 Insufficient cross section of root-pass bead
4 Excessive current for electrode-wire size

Inadequate Penetration

1 Insufficient back gouging
2 Improper edge preparation for arc characteristics (groove too narrow)
3 Insufficient current
4 Excessive voltage
5 Welding speed too high

Incomplete Fusion

1 Improper edge preparation for arc characteristics
2 Arc too long
3 Dirty workpieces or electrode wire
4 Insufficient current

Undercutting

1 Excessive current
2 Welding speed too low
3 Improper electrode-holder angle

Arc-Starting Difficulty

1 Wrong polarity (electrode should be positive)
2 Incomplete welding circuit
3 Inadequate flow of shielding gas
4 Wrong electrode-wire feed rate or welding current

Arc-Length Fluctuations

1 Poor condition of contact tube (rough inner walls, sharp shoulders, contamination by weld spatter)
2 Erratic electrode-wire feed, caused by:
   - Kinked wire (electrode wire should be evenly wound and free of kinks)
   - Excessive or erratic friction in electrode conduit or electrode holder (conduit should be in good condition and of the correct size and length)
   - Clogged contact tubes
   - Unbalance of wire spool
   - Maladjustment of wire-spool brake
   - Poor operation of wire-feed motor or wire straightener
   - Sharp bends in electrode conduit (suspend equipment overhead)
   - Fluctuations in line voltage to wire-feed unit
   - Poor ground connection or burned governor control in wire-feed motor
   - Slippage or insufficient pressure of drive rolls in wire-feed unit

Burnbacks(a)

1 Erratic electrode-wire feed (see causes in item 2 under "Arc-Length Fluctuations")
2 Poor condition of contact tube (see item 1 under "Arc-Length Fluctuations")
3 Incorrect power-supply settings
4 Poor functioning of cooling equipment
5 Poor contact between voltage pickup lead and work

Inadequate Cleaning Action by the Arc

1 Wrong polarity (electrode should be positive)
2 Inadequate gas shielding because of:
   - Insufficient gas flow
   - Spatter on inside of gas nozzle
   - Contact tube off-center in relation to gas nozzle
   - Wrong nozzle-to-work distance
   - Incorrect electrode-holder position (see item 3)
   - Drafty environment (work should be shielded)
3 Incorrect electrode-holder position (should be 7° to 15° forehand)

Dirty Weld Bead(b)

1 Dirty workpieces or electrode wire
2 Impurities in shielding gas (because of air or water leakage)
3 Wrong forehand angle
4 Damaged or dirty gas nozzle
5 Wrong gas-nozzle size (should be smallest possible)
6 Insufficient shielding-gas flow
7 Drafty environment (work should be shielded)
8 Incorrect arc length
9 Contact tube recessed too far (should not be more than ⅛ in. inside gas nozzle)

Rough Weld Bead

1 Unstable arc
2 Improper electrode-holder manipulation
3 Improper current
4 Welding speed too low

Too Narrow Weld Bead

1 Insufficient current
2 Welding speed too high

Too Wide Weld Bead

1 Excessive current
2 Welding speed too low
3 Arc too long

Poor Visibility of Arc and Weld Puddle(c)

1 Wrong position of work
2 Wrong work angle or forehand angle
3 Small, dirty or wrong lens in helmet (a No. 10 or 12 lens should be used)
4 Wrong gas-nozzle size (should be smallest size)

Overheating of Power Supply(d)

1 Excessive power demand (two similar welding machines can be used in parallel if the capacity of one is insufficient)
2 Poor functioning of cooling fan
3 Dirty rectifier stacks (regular maintenance)

Overheating of Cables

1 Loose or faulty connections
2 Cables too small

Overheating of Electrode-Wire Feed Motor

1 Excessive friction between electrode wire and conduit
2 Wrong gear ratio of wire-feed unit
3 Poorly adjusted wire-spool brake
4 Incorrect alignment of gears and rolls in wire-feed unit
5 Worn brushes on wire-feed motor
6 Inadequate capacity of wire-feed motor (high wire-feed rates and large wire sizes require motor of adequate power)
7 Worn or arced governor controls

Operator Fatigue

1 Wrong position of work (weld in flat position whenever possible)
2 Inadequate seating for welder
3 Lack of ventilation
4 Disregard of safety rules in respect to head shield, lens, gloves
5 Weight of cables (reduce by suspending cables overhead)
6 Too many auxiliary operations, such as cleaning and chipping

(a) A burnback occurs when electrode wire fuses to the copper contact tube and wire feed is stopped. It happens when the wire feed is insufficient for the current being used, which causes the arc to lengthen until it overheats the end of the contact tube. An inexperienced welder may get burnbacks while establishing the correct welding conditions.

(b) The appearance of small amounts of black smut in welding with the aluminum-magnesium alloys is not a fault.

(c) The welder must be able to see the arc and the weld puddle at all times.

(d) High demand can damage the power supply by overheating. Overheating is particularly serious with rectifiers.

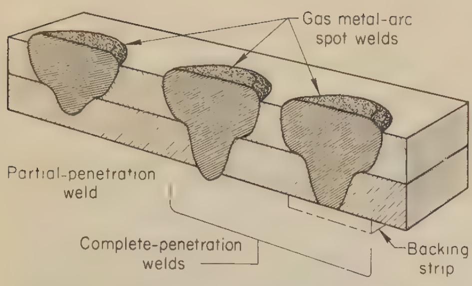


Fig. 26. Shapes of typical gas metal-arc spot welds

weld area. (Starting tabs were not used.) Between passes, the surface of the previously deposited bead was cleaned with a stainless steel wire brush. Interpass temperature was maintained between 150 and 200 F. The tensile strength of the weld repair was essentially the same as that of the original base metal.

Repair welding of castings is more common than repair welding of wrought metal. Most casting repair is done to correct foundry defects or to repair parts broken in service. For example, an alloy 355-T6 piston, 42 in. in diameter and 31 in. high with a thickness that varied from 1 to 3 in., had a large broken area on the top surface and broken areas on the skirt near the compression ring. For repair, the defective areas were chipped to sound unbroken metal, and all surfaces were washed with a solvent cleaner. The casting was then placed in an insulated box and preheated to 300 F by wrapping it with a bead-type resistance heater. For the welding operation, a constant-voltage power supply, a shielding-gas mixture of 75% argon and 25% helium, and a 1/16-in.-diam ER1100 electrode wire were used. Each area of repair was welded without interruption. Adequate weld reinforcement was provided so that the repaired area could be ground flush after cooling. The repairs, five in all, were made with no evidence of cracking, and radiographic inspection showed that they were satisfactory.

Spot Welding by the Gas Metal-Arc Process

Spot welding by the gas metal-arc process is a quick and reliable method of joining aluminum alloy sheet and extrusions. Normally, only enough force is required to hold parts in intimate contact, and only one side of the joint need be accessible. Aluminum alloys can be arc spot welded satisfactorily at high speed (12 or more spots per minute) by unskilled operators.

The cost of gas metal-arc spot welding is approximately half that of riveting, and the spots can develop shear strength and bearing strength equal to or better than those obtained with 5/32-in. 2117-T6 rivets. In addition, fatigue strength is higher than that of riveted joints and resistance spot welded joints. Weld strength and appearance can be varied to suit the job by proper selection of degree of penetration, base-metal alloy and thickness, filler-metal alloy, joint design, fit-up and shielding.

Gas metal-arc spot welding can be used to join all of the arc weldable aluminum alloys and some (for example, 7075 and 7079) whose welding by other arc processes is not recommended (Table 1). A guide to filler-metal selection is given in Table 20. The process is also useful for welding aluminum alloys to steel or copper.

For spot welding, the nozzle assembly on the conventional gas metal-arc welding electrode holder is changed and circuitry is added to provide automatic control of feed, arc, and gas time. After adjusting the current, wire feed and other operating conditions in keeping with the thickness of metal and penetration required, the nozzle is brought into contact with the first member and sufficient pressure is applied to hold the two members in contact. The welding process is started and the electrode wire feeds forward, initiating the arc, which melts through the first member into the second member and forms the spot weld. Crater filling is automatically controlled to obtain a shrink-free spot of the correct shape. The weld usually is made in one second or less.

Reverse-polarity direct current is employed, with argon, helium or argon-helium gas shielding. A pull-type wire feed with a slow run-in control is recommended, to ensure reliable arc starting. A time-lag control between wire-feed shutoff and breaking the welding current prevents the electrode wire from freezing in the weld puddle when the power is cut off.

Constant-voltage power supplies, of either the motor-generator or rectifier type, with adjustable slope control, have been found to give the best results. They are capable of delivering the high current surge required for arc initiation. Constant-current power supplies are not recommended because aluminum electrode wire is likely to ball up on the end when the arc is extinguished.

Gas metal-arc spot welding necessitates the minimum amount of preweld cleaning. Removal of normal oxides

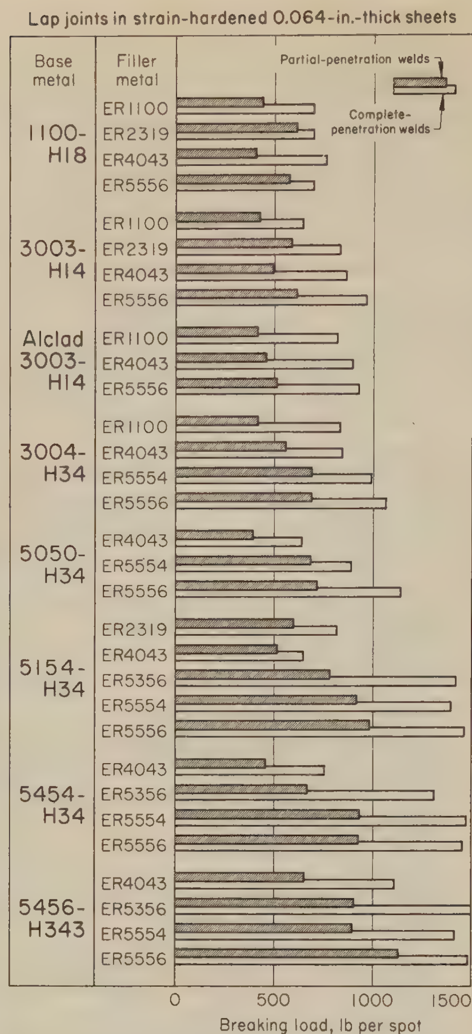


Fig. 27. Tensile-shear breaking loads for gas metal-arc spot welded 0.064-in. sheet

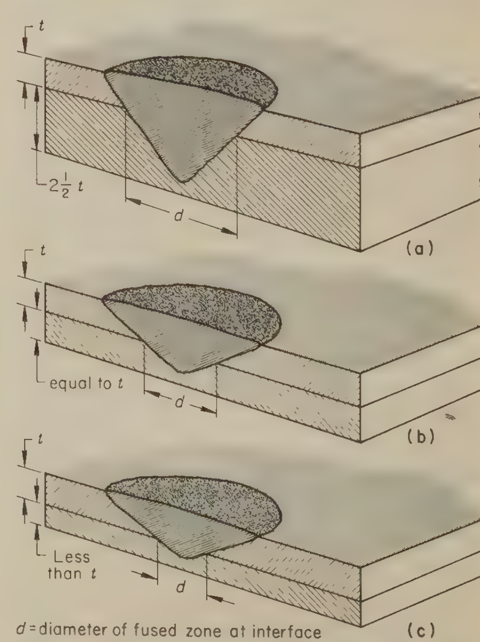


Fig. 28. Relative diameter of fused zones at sheet interface for three combinations of sheet thicknesses

and mill finishes is not necessary unless the ultimate in weld quality is demanded, but anodic and chemical-dip oxide finishes, and lacquers and other insulating coatings, must be removed. Solvent wiping is recommended for the removal of grease and die compounds. Alcohol and toluol are the preferred cleaning agents. Chlorinated solvents such as carbon tetrachloride and trichlorethylene should be used only with thorough ventilation and in an area far remote from the welding area, because they decompose and yield toxic fumes when in the vicinity of an electric arc.

Helium shielding is preferred when welding thin sheet (less than 0.040 in. thick) because its use results in a less sharply pointed weld cone than the use of argon shielding, thus permitting a larger fused area to be made at the faying surfaces. Drawbacks to the use of helium are: it is less readily available than argon, it is more costly, it has a higher level of spatter, and it results in a rougher weld surface. Low gas-flow rates — approximately 20 cu ft per hour — are possible because the spot welding nozzle provides an almost complete enclosure. Gas hoses should be purged with shielding gas before making the first weld in a series. A 5-sec purge is usually sufficient, but a longer purge may be needed at the beginning of the day's work. Once the gas nozzle is purged, successive welds can be made as quickly as the electrode holder can be repositioned.

Aluminum in thicknesses from 0.020 to ¼ in. can be joined by gas metal-arc spot welding. When the first member (usually, the top member) is ⅛ in. thick or less, no special preparation is needed, but if the first member is ⅛ to ¼ in. thick a pilot hole is required. The second member should preferably be at least as thick as the first member, and ideally two to three times as thick. Minimum thickness for the second member is generally 0.030 in. using solid backing; otherwise, it is 0.050 in. Use of chilled or massive backing allows complete penetration through the second member, to achieve maximum nugget diameter and strength.

Spot welds look like slightly crowned buttons on the surface closest to the electrode holder. In cross section, they should be cone-shape and penetrate through, or almost through, the second member. Figure 26 shows the shapes of diametral sections through typical spot welds. For sheets of nearly equal thickness, weld strength is highest when the weld penetrates through the second member. When made against a flat, clean metal backing plate, the spots are flush and uniform, leaving a mark resembling a resistance spot weld. For consistent results, clamping may be necessary to ensure uniform contact at the faying surfaces and between the work and backing. Partial-penetration spot welds show no mark at all on the back surface, and stiffeners and brackets can be welded to the back of architectural panels and other products where appearance is of prime importance, without any marring of the opposite surface.

Gas metal-arc spot welding of aluminum alloys is covered in Table 21.

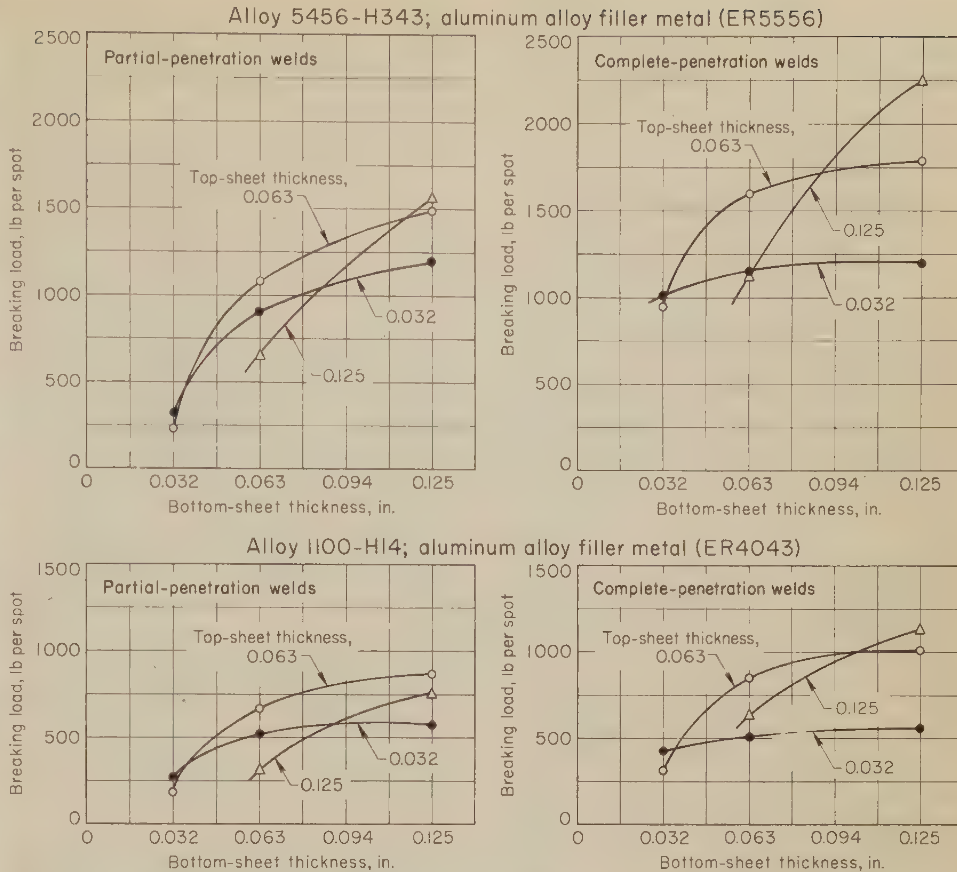


Fig. 29. Effect of sheet thicknesses on tensile-shear breaking load for partial-penetration and complete-penetration gas metal-arc spot welds

The strength of a spot weld is a function of the alloy and the area of the nugget at the interface. Figure 27 shows tensile-shear breaking loads for 0.064-in. sheet of various aluminum alloys with partial-penetration and complete-penetration spot welds. Welds in alloys of the 5*xxx* series have the highest strength. The higher base-metal strength of the heat treatable alloys of series 2*xxx*, 6*xxx* and 7*xxx* is not reflected in the as-spot-welded strength. The combination of alloy 5456 sheet and ER5556 filler metal produces the highest tensile-shear strength per spot weld at a given thickness.

Table 20. Guide to the Choice of Filler-Metal Alloys for Gas Metal-Arc Spot Welding (a)

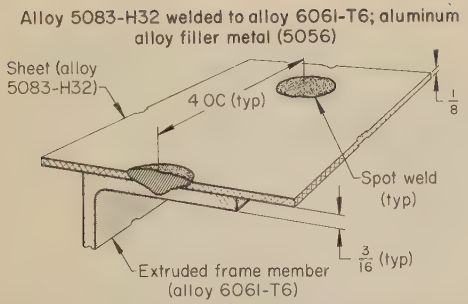
Aluminum base-metal alloys	Good filler-metal alloys(b)	Usable filler-metal alloys(b)
1060, 1100, EC	ER1100, ER4043, ER5556	...
2014, 2024, 2219	ER2319, ER4043, ER4145	...
3003	ER1100, ER4043, ER5556	...
5005, 5050	ER4043, ER5356, ER5556	...
5052, 5083, 5086, 5154, 5456	ER5356, ER5556	ER5554
5454	ER5356, ER5554, ER5556	...
6061, 6063, 6101	ER4043, ER5356, ER5556	ER5554
7075, 7178	ER4043	ER5039, ER5554, ER5556

(a) Based on weld cracking resistance. (b) ER5183 can be used in place of ER5556.

Table 21. Typical Conditions for Gas Metal-Arc Spot Welding of Various Thicknesses of Aluminum Alloy Sheet (a)

Sheet thickness, in.		Partial-penetration welds			Complete-penetration welds		
Top	Bottom	Open circuit voltage, v	Wire feed, ipm(b)	Welding time, sec	Open circuit voltage, v	Wire feed, ipm	Welding time, sec
0.020	0.020	...	...	...	27	250	0.3
0.020	0.030	...	...	...	28	300	0.3
0.030	0.030	25.5	285	0.3	28	330	0.3
0.030	0.050	25.5	330	0.3	31	430	0.3
0.030	0.064	30	360	0.3	31	450	0.3
0.050	0.050	31	385	0.4	32	450	0.4
0.050	0.064	32	400	0.4	32	500	0.4
0.064	0.064	32	420	0.4	32	550	0.5
0.064	0.125	32.5	650	0.5	34.5	675	0.5
0.064	0.187	35	700	0.5	39	700	0.5
0.064	0.250	39	775	0.5	41	800	0.5
0.125	0.125	39.5	800	0.5	41	850	0.6
0.125	0.187	41	850	0.75	41	900	0.75
0.125	0.250	41	900	1.0	...	...	...

(a) Overlap joints; electrode, 0.047-in.-diam ER5554. (b) Welding current (dcrp), in amperes, is approximately equal to one-half wire feed, in inches per minute, of 0.047-in.-diam electrode wire.



Semiautomatic Gas Metal-Arc Spot Welding

Joint type	Lap
Welding position	Flat
Power supply	500-amp, constant-voltage transformer-rectifier
Fixtures	Clamping (when needed)
Electrode holder	500 amp, water cooled
Gas nozzle	¾-in. diam, copper
Electrode wire	1/16-in.-diam alloy 5056(a)
Shielding gas	Argon, at 60 cfh
Electrode stickout	½ in.
Current	610 amp, dcrp
Voltage	32 v
Arc time	58 cycles per spot
Shielding-gas consumption	7 to 10 cu ft/100 spots
Electrode consumption	0.3 to 0.4 lb/100 spots
Production rate	7 to 10 min/100 spots

(a) This electrode wire has been discontinued. See footnote in table with Fig. 22 for information on alternative wires.

Fig. 30. Roof sheet and frame members that were joined by semiautomatic gas metal-arc spot welding (Example 308)

Maximum strength is obtained when the bottom sheet is at least twice the thickness of the top sheet, as the interface will be nearer to the face of the weld nugget and therefore larger (Fig. 28a). When the bottom sheet is about 2½ times thicker than the top sheet, the area of the weld nugget does not vary greatly with small variations in penetration. If the two sheets are of equal thickness (Fig. 28b) or if the top sheet is thicker (Fig. 28c) and if complete penetration cannot be tolerated, the same percentage variation in depth of penetration produces much greater variation in the weld-nugget interface area. If the surface of the bottom sheet is completely penetrated, less variation results in the interface area.

Figure 29 shows the effect of various combinations of top and bottom sheet thicknesses on tensile-shear breaking load per spot, for partial-penetration and complete-penetration spot welds made in alloy 5456-H343 with ER5556 electrode wire and in alloy 1100-H14 with ER4043 electrode wire.

Thicknesses being joined, and strength and appearance requirements, should be considered in determining whether control should be set to produce welds with partial or complete penetration. Welding conditions are easier to establish for complete-penetration welds, and the welds produced will have more uniform strength and appearance. Variability in partial-penetration welds will be reduced if the weld area of the second member is rigidly supported to ensure that the pressure on the first member by the electrode holder will hold the two members in contact.

The two examples that follow describe the use of gas metal-arc spot welding. In the first example, welding was semiautomatic and partial-penetration welds were made through thinner metal into thicker metal. In the second example, welding was automatic and complete-penetration welds were made through thicker metal into backed-up thinner metal.

Example 308. Use of Semiautomatic Gas Metal-Arc Spot Welding for Joining Flat Roofs to Extruded Frame Members (Fig. 30)

In the manufacture of covered railway hopper cars, ⅛-in.-thick 5083-H32 flat roof sheet was laid over 3/16-in.-thick 6061-T6 extruded frame members and welded. Originally, fillet welds were deposited either intermittently or continuously from below, by semiautomatic gas metal-arc welding, but this method was costly and difficult to use on thin material in this position.

Gas metal-arc spot welding was tried. The surfaces to be welded were precleaned by degreasing, and spot welding was done in the flat position through the ⅛-in. roof sheet into the frame member. The pressure of the nozzle of the hand-held electrode holder was usually enough to ensure no gap between the surfaces, but clamping was used when needed to ensure closure.

After spot welding was completed, the perimeter of the roof sheet was manually fillet welded to the car frame to seal against moisture. In addition to their structural functions, the spot welds held the roof sheet firmly in place for the fillet welding. Welding conditions for gas metal-arc spot welding are given in the table that accompanies Fig. 30.

Example 309. Use of Automatic Equipment for Making 700 Spot Welds per Hour by Gas Metal-Arc Welding (Fig. 31)

Gas metal-arc spot welding was used to attach stiffeners to sidewalls and roofs in the welding of 30-ft-long cargo containers for shipboard transportation. Other subsequent welding operations were required to join the wall and roof panels to floor assemblies, siderails, and corner posts to make a leakproof container.

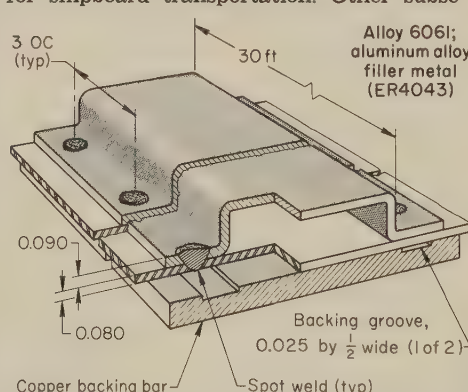
Joining the stiffeners (extrusions) to the roof (sheet) by resistance spot welding was impractical, because the large size of the roof panels would have necessitated the provision of a welding machine with an excessively deep throat. Joining by riveting would have been expensive and would have required the sealing of each rivet hole. The cost of gas metal-arc spot welding, including labor, consumable supplies, and amortization of equipment, was estimated to be about half the cost of joining by riveting.

Wall and roof panels were made of 0.060 to 0.080-in.-thick 6061-T6 sheet; the stiffeners were hat-shape extruded sections, 0.080 to 0.090 in. thick, of 6061-T6. Because more than 4200 spot welds were to be made on each container and many containers were to be made, special mechanized welding equipment and controls were constructed. A gantry-type assembly that housed 14 spot welding electrode holders rode over the work on two siderails. An operator indexed it over a stiffener and then the control unit automatically actuated groups of four electrode holders in a predetermined sequence designed to minimize distortion of the panel. The electrode holders applied 40 psi pressure to the work to clamp the extrusions and sheet together. After a stiffener was welded in place, the gantry assembly was indexed about 18 in. to the next stiffener and the operation was repeated.

A 75% helium, 25% argon shielding-gas mixture and 1/16-in.-diam ER4043 electrode wire were selected to prevent weld crater cracking. No precleaning was required.

Copper backing bars with a relief groove under the welds were used to ensure good metal-to-metal contact during welding and to allow controlled full penetration for maximum strength. The backing bar was also essential because the thicknesses of the two pieces of metal being welded were unequal and because welding was being done through the thicker piece into the thinner piece, which is more difficult than the opposite arrangement.

All penetration nuggets were ground off to meet interior-smoothness requirements (no retention of any particle larger than 300 mesh). Shear strength in excess of 700 lb per spot was consistently obtained. Other processing data are given in the table that accompanies Fig. 31.



Automatic Gas Metal-Arc Spot Welding

Joint type	Lap
Welding position	Flat
Power supply	500-amp, constant-voltage transformer-rectifier, with variable slope and inductance
Fixtures	Pneumatic clamping; copper backing bar
Electrode-holder clamping pressure	400 psi
Electrode holder	500 amp, water cooled
Gas nozzle	1-in. diam, copper
Electrode wire	1/16-in.-diam ER4043
Shielding gas	75% helium, 25% argon, at 50 cfh
Electrode stickout	⅝ in.
Current	325 amp, dcrp
Voltage	28 v
Arc time	About 30 cycles(a)
Shielding-gas consumption	About 1 cu ft/100 spots
Electrode consumption	About 0.0743 lb/100 spots
Production rate	About 700 spots/hour(b)

(a) Depending on the metal thickness being joined. (b) Includes indexing of gantry and loading and unloading of work.

Fig. 31. Joining stiffeners to panels for a cargo container by automatic gas metal-arc spot welding (Example 309)

Gas Metal-Arc Spot Welding Aluminum to Other Metals. In gas metal-arc spot welding of aluminum alloys to other metals, the brittle intermetallic compounds formed at the periphery of the welds have little effect on strength and ductility in shear loading, which permits fusion spot welding of metal combinations that cannot be welded along seam joints without the use of special techniques.

When the other metal is thin, the weld can be made by melting through it with the arc. The in-rushing aluminum alloy filler metal and the force of the arc push the other metal away from the center of the weld so that the core and crown are composed of relatively ductile aluminum. The maximum thickness of the other metal that can be handled in this way is about 0.030 in. A pilot hole (about ¼ in. in diameter) through the nonaluminum member improves performance by providing a path for the filler metal, so that it remains undiluted and ductile. Pilot holes are essential when the other metal is more than 0.030 in. thick.

With a filler metal suitable for fusion welding the other metal, joints

can be made in which the bottom member is the other metal. These filler metals usually have higher melting points than aluminum, though, and a superior joint is obtained if the aluminum is sandwiched between two pieces of the other metal. Three-layer joints of this type, with copper outer members and aluminum in the middle (see Fig. 32), are useful in making permanent connections in electrical applications.

Two or more pieces of aluminized steel can be joined by gas metal-arc spot welding, using an aluminum alloy filler metal and a backing strip of aluminum beneath the bottom steel sheet. In this joint, only the aluminum is exposed to the environment.

Gas Tungsten-Arc Welding

The advantages of welding aluminum alloys by the gas tungsten-arc process are the same as for other metals, as discussed in the article on Gas Tungsten-Arc Welding, which begins on page 113 of this volume.

Welding can be done with or without filler metal, but because filler metal is often used, there must be access at the joint for both torch and filler metal.

Thicknesses of aluminum alloys commonly welded by the gas tungsten-arc process range from 0.040 to ⅜ in. for manual welding and from 0.010 to 1 in. for automatic welding. Gas tungsten-arc welding is especially suitable for the automatic welding of thin workpieces that require the utmost in quality or finish, because of the precise heat control possible and the ability to weld with or without filler metal. Metal thicker than ⅜ in. can be manually welded; however either gas metal-arc or automatic tungsten-arc welding is preferred.

Power Supply and Equipment. For joining aluminum alloys, gas tungsten-arc welding utilizes either alternating or direct current. Both straight and reverse polarity are used with direct-current welding. The same power supplies, arc-stabilization accessories, torches, and control systems as are used for gas tungsten-arc welding of other metals are used for aluminum (see the article on Gas Tungsten-Arc Welding, page 113). Single-phase alternating-current welding transformers should have an open-circuit voltage of 80 to 100 volts.

The oxide layer on the surface of aluminum alloys gives rise to some arc rectification during the reverse-polarity half of the alternating-current cycle. This arc rectification, either partial or complete, is undesirable, because it results in poor arc stability and possible overheating of the transformer; it can be overcome by the use of condensers in the welding circuit or preferably by placing a battery bias in series with the welding circuit. Battery power of 6 to 8 volts is usually sufficient to balance the current. The positive terminal should be in the direction of the electrode. About 100 amp-hr of storage-battery capacity should be used with every 100 amp of welding current. If two or more batteries are needed to obtain the required ampere-hour electrical capacity, they should be connected in parallel.

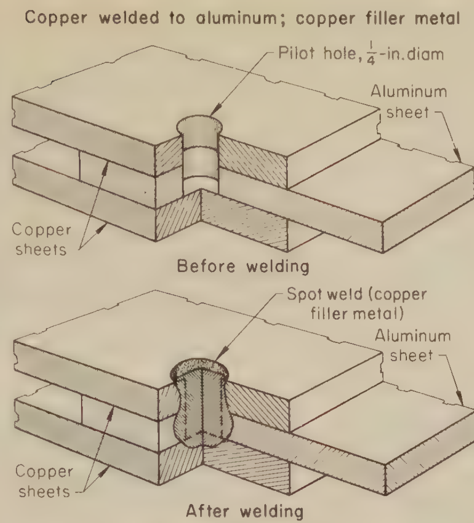


Fig. 32. Gas metal-arc spot weld with copper filler metal joining copper-aluminum-copper sandwich

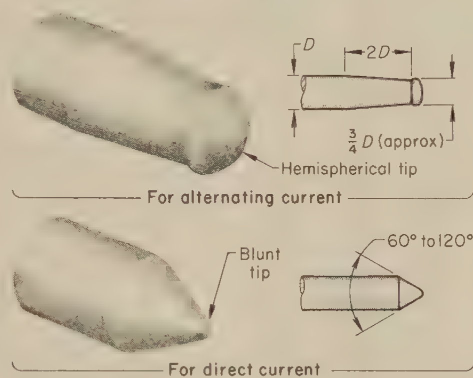


Fig. 33. Electrode tips used for gas tungsten-arc welding of aluminum alloys

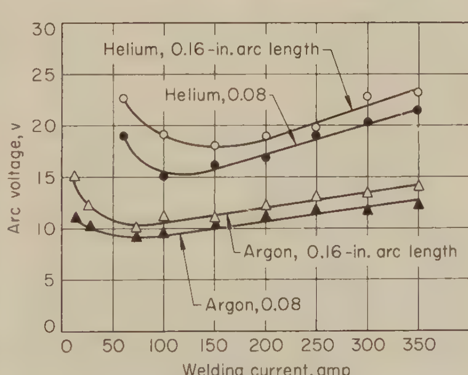


Fig. 34. Arc-voltage characteristics of argon and helium shielding gas in gas tungsten-arc welding of aluminum alloys

Electrodes for Gas Tungsten-Arc Welding

For alternating-current gas tungsten-arc welding, unalloyed tungsten and tungsten-zirconium electrodes are recommended. Zirconiated electrodes are less likely to be contaminated by aluminum and have a slightly higher current rating. Unalloyed tungsten electrodes minimize inclusions in the weld bead and current unbalance.

Electrodes of 1% thoriated tungsten, which have higher current capacity than unalloyed tungsten and cost less than zirconiated electrodes, are also used; their main disadvantage for alternating-current welding is a slight tendency to drip. This drip will result in some tungsten inclusions in the weld metal. With a skilled operator and good equipment, the inclusions are small and well dispersed. For best results with 1% thoriated electrodes, the electrode should have a ground surface. Electrodes of 2% thoriated tungsten are not generally used for alternating-current welding of aluminum alloys.

When gas tungsten-arc welding aluminum with alternating current, the tip of the electrode should be hemispherical, as shown in Fig. 33. The tip is prepared by using an electrode one size larger than required for the welding current, taper grinding the tip and forming the hemispherical end by welding for a few seconds with a current 20 amp higher than needed, holding the electrode vertically up.

Thoriated tungsten electrodes are normally used for direct-current gas tungsten-arc welding of aluminum. The tip of the electrode should be ground to a blunt conical point, having an included angle between 60° and 120° as shown in Fig. 33, to attain maximum penetration.

When an electrode becomes contaminated with aluminum, it must be replaced or cleaned. Minor contamination can be burned off by increasing the current while holding the arc on a piece of scrap metal. Severe contamination can be removed by grinding or by breaking off the contaminated portion of the electrode and re-forming the correct electrode contour on a piece of scrap aluminum.

Shielding Gases for Gas Tungsten-Arc Welding

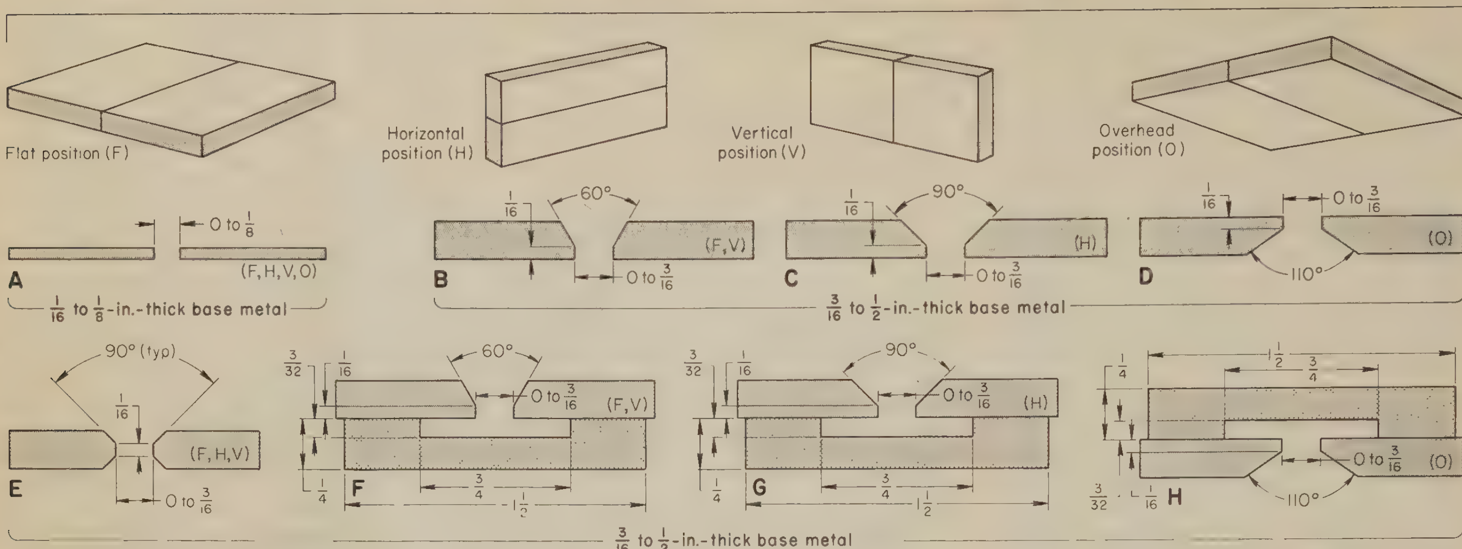
Argon, helium, and mixtures of argon and helium are used as shielding gases in the gas tungsten-arc welding of aluminum alloys. The selection is somewhat dependent on the type of current used.

Welds made with alternating current show little difference in soundness or strength whether made with argon or helium shielding. With helium shielding, penetration is deeper; hence helium is sometimes employed with higher speeds and for thicker sections. Also, the welds develop slightly higher mechanical properties. However, argon is used more, for the following reasons:

1 It is more readily available and costs less than helium.
2 It affords better control of the weld puddle.
3 It gives a smoother, quieter arc, greater arc cleaning action, and easier arc starting.
4 Less gas is required for a specific application.
5 It has better cross-draft resistance than helium.
6 There is less clouding, and the metal stays brighter. The operator can see the weld puddle more easily.

With argon shielding, the arc voltage is lower for a given current value and arc length, as shown in Fig. 34. The lower arc-voltage characteristic of argon is essential to the successful manual alternating-current welding of

Table 22. Typical Conditions for Manual Gas Tungsten-Arc Welding of Butt Joints, Using Alternating Current(a)



Metal thickness, in.	Joint design (see above)	Welding position(b)	Electrode diameter, in.	Filler metal: Diameter, in.	Filler metal: Used per 100 ft, lb	Argon: Nozzle diameter, in.	Argon: Flow, cfh	Current (ac), amp	Number of passes
1/16	A	F	1/16	3/32	1/2	3/8	20	70	1
	A	H, V	1/16	3/32	1/2	3/8	20	70	1
	A	O	1/16	3/32	1/2	3/8	25	60	1
3/32	A	F	3/32	1/8	1	3/8	20	95	1
	A	H, V	3/32	3/32	1	3/8	20	85	1
	A	O	3/32	3/32	1	3/8	25	90	1
1/8	A	F	1/8	1/8	2	7/16	20	125	1
	A	H, V	3/32	1/8	2	3/8	20	115	1
	A	O	3/32	1/8	2	3/8	25	120	1
3/16	B	F	1/8	5/32	4½	7/16	25	175	2
	C	H	1/8	5/32	4½	7/16	25	160	2
	B	V	1/8	5/32	4½	7/16	25	160	2
	D	O	1/8	5/32	5	7/16	30	170	2
1/4	B	F	3/16	3/16	8	1/2	30	225	2
	C	H	5/32	3/16	8	1/2	30	200	2
	B	V	5/32	3/16	8	1/2	30	200	2
	D	O	3/16	3/16	10	1/2	35	215	2
3/8	B	F	1/4	3/16	15½	5/8	35	325	2
	E	F	1/4	3/16	14	5/8	35	360	2
	F	F	1/4	3/16	15½	5/8	35	325	3
3/8 ..... (cont)	C	H	3/16	3/16	22	5/8	35	250	3
	E	H	3/16	3/16	14	5/8	35	260	2
	G	H	3/16	3/16	15½	5/8	35	250	4
	B	V	3/16	3/16	22	5/8	35	250	3
	E	V	3/16	3/16	14	5/8	35	260	2
	F	V	3/16	3/16	15½	5/8	35	250	4
	D	O	3/16	3/16	32	5/8	40	275	3
	H	O	3/16	3/16	32	5/8	40	275	3
1/2	B	F	1/4	3/16	30	5/8	35	350	3
	E	F	1/4	3/16	30	5/8	35	400	3
	F	F	1/4	3/16	30	5/8	35	350	4
	C	H	3/16	3/16	43	5/8	35	260	3
	E	H	3/16	3/16	30	5/8	35	270	3
	G	H	3/16	3/16	30	5/8	35	260	4
	B	V	3/16	3/16	43	5/8	35	260	3
	E	V	3/16	3/16	30	5/8	35	270	3
	F	V	3/16	3/16	30	5/8	35	260	4
	D	O	1/4	3/16	55	5/8	40	280	3
	H	O	1/4	3/16	55	5/8	40	280	4

(a) Welding speed is 8 in. per minute for all metal thicknesses except 1/8 and 3/16 in., for which it is 10 in. per minute. Preheat is not required for metal through 3/16 in. thick; it is optional for 1/4-in.-thick metal; for welding 3/8-in.-thick metal in the flat position, it is up to 400 F; for welding 3/8-in.-thick metal in the other positions and for welding 1/2-in.-thick metal in all positions, it is up to 600 F. (b) F = flat; H = horizontal; V = vertical; O = overhead.

extremely thin material, because it decreases the probability of burn-through. This same characteristic is advantageous in vertical and overhead welding, because the molten metal is less likely to sag or run.

In special applications, where a balance of characteristics is desired, a mixture of argon and helium is used with alternating-current welding.

Argon is preferred for reverse-polarity direct-current welding because it establishes an arc more easily and provides better arc control.

Helium or an argon-helium mixture is always used with straight-polarity direct-current welding of aluminum. It assists in providing the deep, narrow penetration essential for the best properties and a minimum heat-affected zone. Helium shielding also prevents development of the rippled surface typical of argon shielding and straight-polarity direct-current welding.

When aluminum is welded with alternating current or reverse-polarity direct current, a white band of varying width appears alongside the weld bead. This white band, disclosed by one analysis to be aluminum oxide, never occurs when welding is done with straight-polarity direct current, and it is believed to be caused by the emission of electrons from the surface of the aluminum when it is on the cathode side of the arc (dcrp). The electrons leave the aluminum through the aluminum oxide, thus serving to detach the oxide from the surface.

When the white band alongside the weld is of hairline width immediately adjacent to the weld bead itself, the flow of shielding gas is adequate for proper shielding of the tungsten arc. Any increase in gas flow will cause widening of the band, indicating that gas is being wasted.

Filler Metals for Gas Tungsten-Arc Welding

Gas tungsten-arc welding can be done with or without filler metal. Sometimes the joint design permits the base metal to provide the weld metal. In some square-groove butt joints, the weld metal comes from the straight sides of the groove, or extra metal may be provided on a corner or flange that is melted to form the weld. If restraint is likely to cause cracking, best results are achieved by the addition of separate filler metal.

Usually, filler metal is added in the form of a bare rod for manual welding or as a coil of wire for automatic feeding. The filler-metal alloys used for gas-shielded arc welding of aluminum are discussed earlier in this article (see page 296) and are listed in Table 3. Suitability of the various filler metals for use with different aluminum alloys, and for different properties, is given in Tables 4, 5 and 6.

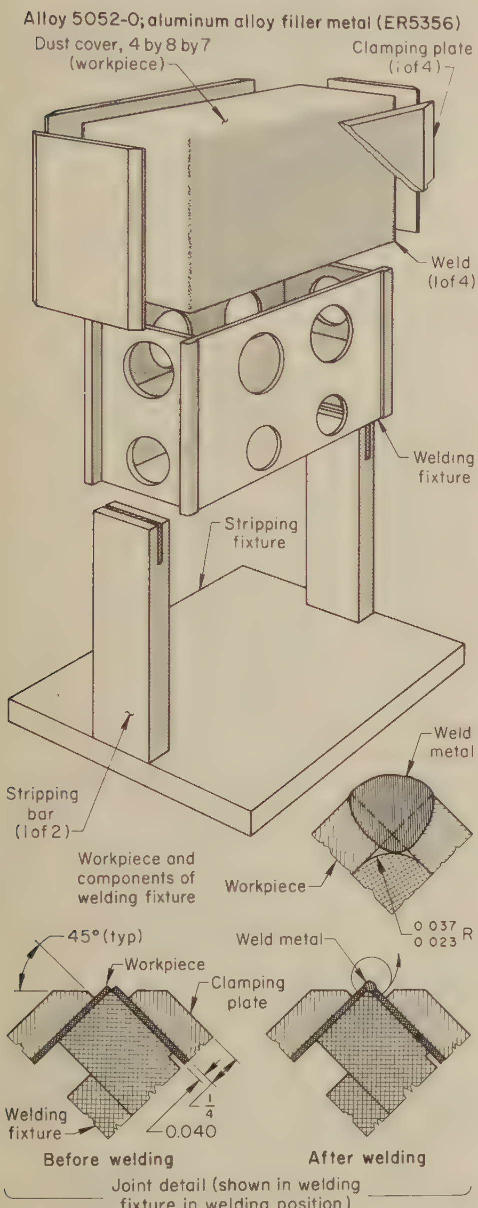
Filler-metal rod and wire comes in a wide range of sizes. Straight lengths of rod (36 in. long), packaged in tubes containing 5 lb of filler metal, are available in diameters of 1/16, 3/32, 1/8, 5/32, 3/16 and 1/4 in. from regular stock, and rod in diameters of 0.030, 0.035, 0.040, and 3/64 is available on special order. Wire is available in 1-lb and 10-lb spools in sizes from 0.030 to 0.040 in. in diameter and in 1-lb and 15-lb spools in sizes from 3/64 to 1/8 in. in diameter.

Weld Backing in Gas Tungsten-Arc Welding

Backing bars are commonly used when butt welds are made from one side only, but they are usually not necessary in automatic straight-polarity

direct-current welding of square-groove butt joints from one side only.

Temporary backing bars are shown with the butt welds in Table 22. Permanent backing bars like those shown in Table 17 and described in Example 297 (for gas metal-arc welding) are also applicable to gas tungsten-arc welding. For additional discussion of backing bars, see the section on Weld Backing for Gas Metal-Arc Welding.



Manual AC Gas Tungsten-Arc Welding

Joint type	Corner
Weld type	Fillet
Welding position	Flat
Power supply	40 v, 320 amp, high-frequency stabilization
Fixtures	Internal fixture, clamping plates, clamps
Torch	Water cooled
Electrode	3/32-in.-diam EWTh-2
Filler metal	1/16-in.-diam ER5356
Shielding gas	Argon, at 20 cfh
Current	170 amp, ac
Number of passes	One
Production rate	3 cans per hour

Fig. 35. Module can made of 0.040-in.-thick alloy 5052-O that was welded with negligible distortion because of careful fixturing and process control (Example 310)

Table 23. Typical Conditions for Manual AC Gas Tungsten-Arc Welding of Corner Joints

Metal thickness, in.	Welding position (a)	Electrode diameter, in.	Filler metal: Diameter, in.	Filler metal: Used per 100 ft, lb	Argon: Nozzle diameter, in.	Argon: Flow, cfh	Current (ac), amp	Welding: Preheat	Welding: Speed, ipm	Welding: Number of passes
1/16	F	1/16	3/32	1/2	3/8	20	60	None	10	1
	H, V	1/16	3/32	1/2	3/8	20	60	None	10	1
	O	1/16	3/32	1/2	3/8	25	60	None	10	1
3/32	F	3/32	1/8	1	3/8	20	90	None	10	1
	H, V	3/32	1/8	1	3/8	20	90	None	10	1
	O	3/32	1/8	1	3/8	25	90	None	10	1
1/8	F	1/8	1/8	2	3/8	20	115	None	10	1
	H, V	3/32	1/8	2	3/8	20	115	None	10	1
	O	3/32	1/8	2	3/8	25	115	None	10	1
3/16	F	1/8	5/32	4½	7/16	25	160	None	10	1
	H, V	1/8	5/32	4½	7/16	25	160	None	10	1
	O	1/8	5/32	4½	7/16	30	170	None	10	1
1/4	F	5/32	3/16	7	1/2	30	210	Optional	8	2
	H, V	5/32	3/16	7	1/2	30	200	Optional	8	1
	O	3/16	3/16	7	1/2	35	215	Optional	8	1
3/8	F	3/16	3/16	17	5/8	35	280	Optional	8	2
	H, V	3/16	3/16	17	5/8	35	250	Optional	8	2
	O	3/16	3/16	17	5/8	40	260	Optional	8	3
1/2	F	3/16	3/16	30	5/8	35	290	Optional	8	3
	H, V	3/16	3/16	30	5/8	35	260	Optional	8	3
	O	3/16	3/16	30	5/8	40	280	Optional	8	3

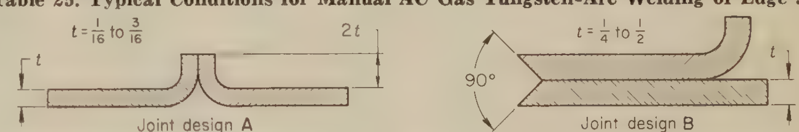
(a) F = flat; H = horizontal; V = vertical; O = overhead

Table 24. Typical Conditions for Manual AC Gas Tungsten-Arc Welding of T and Lap Joints

Metal thickness, in.	Welding position (a)	Electrode diameter, in.	Filler metal: Diameter, in.	Filler metal: Used per 100 ft, lb	Argon: Nozzle diameter, in.	Argon: Flow, cfh	Current (ac), amp	Welding: Preheat temperature, F	Welding: Speed, ipm	Welding: Number of passes
1/16	F	1/16	3/32	1/2	3/8	20	80	None	8	1
	H, V	1/16	3/32	1/2	3/8	20	80	None	8	1
	O	1/16	3/32	1/2	3/8	25	70	None	8	1
3/32	F	1/8	3/32	1	3/8	20	120	None	8	1
	H, V	3/32	3/32	1	3/8	20	100	None	8	1
	O	3/32	3/32	1	3/8	25	110	None	8	1
1/8	F	1/8	1/8	2	7/16	20	150	None	10	1
	H, V	3/32	1/8	2	3/8	20	120	None	8	1
	O	3/32	1/8	2	3/8	25	135	None	8	1
3/16	F	5/32	5/32	4½	1/2	25	215	None	8	1
	H, V	1/8	5/32	4½	7/16	25	180	None	8	1
	O	5/32	5/32	4½	7/16	30	190	None	8	1
1/4	F	3/16	3/16	7	1/2	30	260	Optional	8	1
	H, V	3/16	3/16	7	1/2	30	235	Optional	8	1
	O	3/16	3/16	7	1/2	35	240	Optional	8	1
3/8	F	1/4	3/16	17	5/8	35	345	Up to 400	8	2
	H, V	3/16	3/16	17	5/8	35	290	Up to 600	8	2
	O	3/16	3/16	17	5/8	40	290	Up to 600	8	3
1/2	F	1/4	3/16	30	5/8	35	375	Up to 600	8	3
	H, V	1/4	3/16	30	5/8	35	300	Up to 600	8	3
	O	1/4	3/16	30	5/8	40	310	Up to 600	8	3

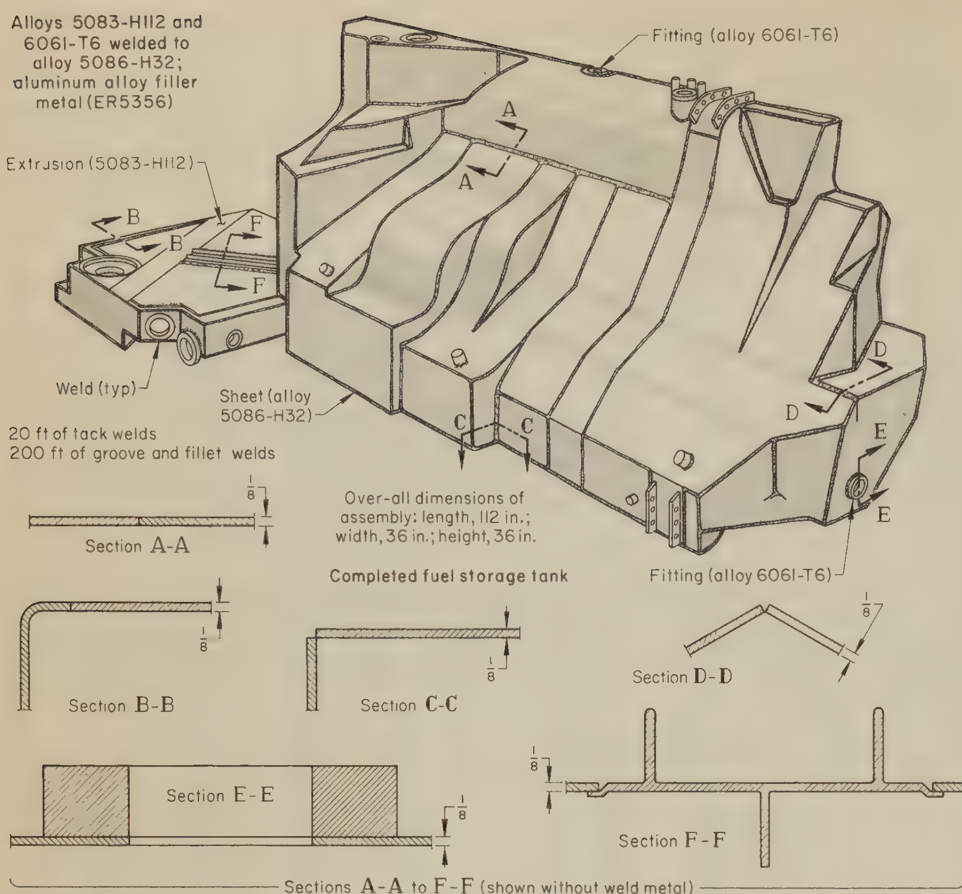
(a) F = flat; H = horizontal; V = vertical; O = overhead

Table 25. Typical Conditions for Manual AC Gas Tungsten-Arc Welding of Edge Joints



Metal thickness, t, in.	Welding position (a)	Electrode diameter, in.	Filler metal: Diameter, in.	Filler metal: Used per 100 ft, lb	Argon: Nozzle diameter, in.	Argon: Flow, cfh	Current (ac), amp	Welding: Preheat	Welding: Speed, ipm	Welding: Number of passes
				Joint Design A						
1/16	F	1/16	3/32	3/4	3/8	20	55	None	10	1
	H, V	1/16	3/32	3/4	3/8	20	55	None	10	1
	O	1/16	3/32	3/4	3/8	25	55	None	10	1
3/32	F	3/32	1/8	2	3/8	20	85	None	10	1
	H, V	3/32	1/8	2	3/8	20	80	None	10	1
	O	3/32	1/8	2	3/8	25	85	None	10	1
1/8	F	3/32	1/8	4	3/8	20	110	None	10	1
	H, V	3/32	1/8	4	3/8	20	100	None	10	1
	O	3/32	1/8	4	3/8	25	100	None	10	1
3/16	F	1/8	5/32	8	7/16	25	150	None	10	1
	H, V	1/8	5/32	8	7/16	25	150	None	10	1
	O	1/8	5/32	8	7/16	30	160	None	10	1
				Joint Design B						
1/4	F	5/32	5/32	15	1/2	30	200	Optional	8	1
	H, V	5/32	5/32	15	1/2	30	190	Optional	8	1
	O	5/32	5/32	15	1/2	35	200	Optional	8	1
3/8	F	3/16	3/16	33	5/8	35	270	Optional	8	1
	H, V	3/16	3/16	33	5/8	35	230	Optional	8	2
	O	3/16	3/16	33	5/8	40	250	Optional	8	3
1/2	F	3/16	3/16	60	5/8	35	275	Optional	8	3
	H, V	3/16	3/16	60	5/8	35	240	Optional	8	3
	O	3/16	3/16	60	5/8	40	260	Optional	8	3

(a) F = flat; H = horizontal; V = vertical; O = overhead



Conditions That Were the Same for All Joints(a)

Welding process . . Manual gas tungsten-arc (ac)	Electrode 3/32-in.-diam EWTh-1
Power supply . . 200-amp transformer, continuous high-frequency stabilization, 60% duty cycle	Filler metal 1/8-in.-diam ER5356
Torch . . . . . 200 amp, water cooled	Shielding gas . . . . . Argon, at 15 to 20 cfh
Gas nozzle . . . . . 7/16-in. diam	Voltage . . . . . 20 to 26 v
	Number of passes . . . . . One

Conditions That Varied With Joint

Joint	Type	Weld	Welding position(b)	Current (ac), amp	Alloys joined
A-A, B-B	Butt	Square groove	F, V	100-140	5086 to 5086
C-C	Corner	Fillet	F, H, V	110-160	5086 to 5086
D-D	Corner	V-groove	F	100-140	5086 to 5086
E-E	T	Fillet	H	110-160	5086 to 6061
F-F	Butt	Single-bevel groove	F, V	120-160	5086 to 5083

(a) For precleaning and tack welding procedures, see Examples 293 and 305, respectively. (b) F = flat; H = horizontal, V = vertical.

Fig. 36. Fuel tank for an M-60 combat tank, and types of welded joints (Example 311)

Alternating-Current Gas Tungsten-Arc Welding

Almost all manual and automatic gas tungsten-arc welding of aluminum alloys 0.040 through 3/8 in. thick is done with balanced-wave alternating-current high-frequency-stabilized power supplies, argon shielding gas, and unalloyed tungsten electrodes. Zirconiated tungsten electrodes and helium and argon-helium shielding-gas mixtures are also used with alternating-current welding for reasons discussed earlier, in the sections on Electrodes for Gas Tungsten-Arc Welding and on Shielding Gases for Gas Tungsten-Arc Welding. Adequate gas shielding is indicated by the bright silvery band bordering each side of the weld bead (also discussed earlier) and a shiny bead.

Usually, alternating-current welding provides the optimum combination of current-carrying capacity, arc controllability, and arc cleaning action for the welding of aluminum alloys. A short arc length must be maintained in order to obtain sufficient penetration and to prevent undercutting, excessive width of weld bead, and consequent loss of control of penetration and weld contour. Arc length should be about equal to the diameter of the tungsten electrode. On fillet welds, a short arc and adequate current are needed to prevent bridging the root. A short arc also ensures that the inert gas completely surrounds the weld as it forms.

Manual Welding. Typical conditions for manual alternating-current gas tungsten-arc welding are given in Tables 22 to 25. Metal that is more than 1/8 in. thick is grooved to ensure complete penetration. A single-V groove with an included angle of 60° to 90° is the most often used. Under certain conditions, a double-V groove may be advantageous for metal more than 1/4 in. thick. If the operator has difficulty in maintaining a very short arc, a larger included angle or joint spacing may be required in order to allow a longer arc to be used.

The arc should not be started by touching the tungsten electrode to the aluminum workpiece, because this may mark the work or result in aluminum being picked up on the electrode, which is likely to cause a wild, uncontrollable arc and a dirty weld. The initial arc should be struck on a starting block to heat the electrode to its operating temperature. (The arc should never be struck on a piece of carbon, as this will contaminate the electrode.) The arc is then broken and reignited at the joint. This technique reduces the likelihood of forming tungsten inclusions at the start of the weld, which can happen when a cold electrode is used to start the weld.

The arc is struck like striking a match — by swinging the electrode holder in a pendulum-like motion toward the starting place. With superimposed high-frequency current for arc stabilization, there is no need to touch the work with the electrode as the arc will start when the electrode tip is brought close to the work surface. Some machines apply the high frequency only when starting; others have it on continuously, or have a switch that permits the operator to cut it on or off at will. The arc is held at the starting point until the metal liquefies and a weld puddle is established. Establishment and maintenance of a suitable weld puddle is important and welding must not proceed ahead of the puddle. A separate foot-operated heat control, available with certain power supplies, is highly advantageous in preventing uneven penetration by permitting the current to be adjusted as the work becomes hotter. Breaking the arc also requires special care, to prevent the formation of shrinkage cracks in the weld crater. Several techniques are used. The arc can be gradually lengthened while filler metal is added to the crater; the arc can be quickly broken and restruck several times while adding filler metal to the crater; or a foot control can be used to reduce current at the end of the weld. Crater-filling devices may be used if properly adjusted and timed.

By using these techniques, and adequate fixturing, weld joints can be made manually in aluminum alloys down to 0.040 in. thick, without excessive distortion. This is shown in the following example.

Example 310. Maintaining Close Dimensional Tolerances During Manual Gas Tungsten-Arc Welding of Thin Aluminum Sheet (Fig. 35)

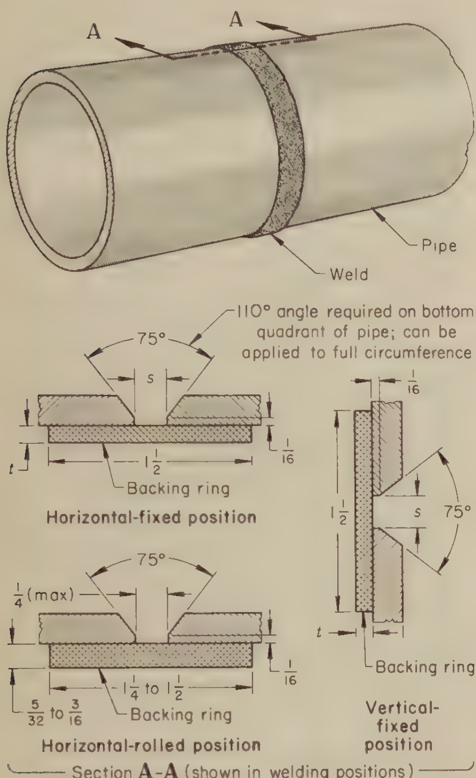
The open-end module can shown in Fig. 35, which served as a dust cover and a heat sink for electronic gear, was made from a single sheet of 0.040-in. aluminum alloy 5052-O by brake bending the bottom corners and manually welding the four vertical corner joints. Tolerances of ±0.01 to ±0.02 in. were necessary to ensure close fit over components for heat-sink efficiency.

To meet the tolerances, alternating-current gas tungsten-arc welding and ER5356 filler metal were selected, and a box-shape fixture was constructed that consisted of four 1/2-in.-thick steel plates joined so as to match the internal dimensions of the can. The fixture was tapered so that the can was slightly under dimension at the

closed end, and slightly over dimension at the open end.

The sequence of operations for welding was as follows:

1 After the can was formed and chemically cleaned, the fixture was inserted.
2 Four ¼-in.-thick plates of a size to leave access for welding the four vertical corners of the can were placed against the outer surfaces of the four sides of the can and clamped to the fixture through the end.
3 The corner joints were welded in the flat position (slightly downhill) on a welding table by the manual gas tungsten-arc process. (Welding conditions are given in the table that accompanies Fig. 35.)
4 The clamping plates were removed, leaving the can held on the fixture by shrinkage.
5 The can and fixture were placed on raised supports, the can was heated with an oxyacetylene torch, the can expanded, and the fixture dropped free.



Root opening, *s*, is zero with no backing ring or with a removable backing ring, and ¼ in. max with an integral backing ring. For thickness of backing ring (*t*) for fixed-position welding, see Table 26.

Fig. 37. Edge preparation for fixed-position pipe welding using the typical conditions given in Table 26

Table 26. Typical Conditions for Fixed-Position Pipe Welding by the Manual Alternating-Current Gas Tungsten-Arc Process, Using Joint Designs Shown in Fig. 37

Nominal pipe size, in.	Wall thickness, in.	Thickness of backing ring (t in Fig. 37), in.	Electrode diameter, in.	Filler-metal diameter, in.	Gas-nozzle diameter, in.	Argon flow, cfh	Current (ac), amp	Number of passes(a)
Horizontal-Fixed Position								
1	0.133	0.072	⅛	3/32	½	30 to 80	90 to 110	1 to 2
1¼	0.140	0.072	⅛	⅛	½	30 to 80	100 to 120	1 to 2
1½	0.145	0.072	⅛	⅛	½	30 to 80	110 to 130	1 to 2
2	0.154	0.093	⅛	⅛	½	30 to 80	120 to 140	1 to 2
2½	0.203	0.093	⅛	⅛	½	30 to 80	130 to 150	2
3	0.216	0.093	⅛	⅛	½	30 to 80	145 to 165	2
3½	0.226	0.093	⅛	⅛	½	30 to 80	150 to 170	2
4	0.237	0.125	3/16	⅛ to 3/16	½	35 to 80	160 to 180	2
5	0.258	0.125	3/16	5/32 to 3/16	½	35 to 80	180 to 190	2
6	0.280	0.187	3/16	5/32 to 3/16	½	50 to 80	195 to 205	2
8	0.322	0.187	3/16	5/32 to 3/16	½	50 to 80	210 to 220	2 to 3
10	0.365	0.187	3/16	5/32 to 3/16	½	50 to 80	230 to 240	2 to 3
12	0.406	0.187	3/16	5/32 to 3/16	½	50 to 80	245 to 255	2 to 3
Vertical-Fixed Position								
1	0.133	0.072	⅛	3/32	7/16	25 to 50	95 to 115	1 to 2
1¼	0.140	0.072	⅛	⅛	7/16	25 to 50	105 to 125	1 to 2
1½	0.143	0.072	⅛	⅛	7/16	25 to 50	115 to 135	1 to 2
2	0.154	0.093	⅛	⅛	7/16	30 to 60	125 to 145	2 to 3
2½	0.203	0.093	⅛	⅛	7/16	30 to 60	135 to 155	3 to 5
3	0.216	0.093	⅛	⅛	½	40 to 60	150 to 170	3 to 5
3½	0.226	0.093	⅛	⅛	½	40 to 60	155 to 175	3 to 5
4	0.237	0.125	3/16	⅛ to 5/32	½	40 to 60	165 to 185	3 to 5
5	0.258	0.125	3/16	5/32 to 3/16	½	50 to 60	185 to 205	3 to 5
6	0.280	0.187	3/16	5/32 to 3/16	½	50 to 60	200 to 220	3 to 5
8	0.322	0.187	3/16	5/32 to 3/16	½	60 to 80	215 to 235	5 to 8
10	0.365	0.187	3/16	5/32 to 3/16	½	60 to 80	235 to 255	5 to 8
12	0.406	0.187	3/16	5/32 to 3/16	½	70 to 80	250 to 270	6 to 8

(a) For horizontal-fixed position, more passes are required for the bottom quadrant of the joint.

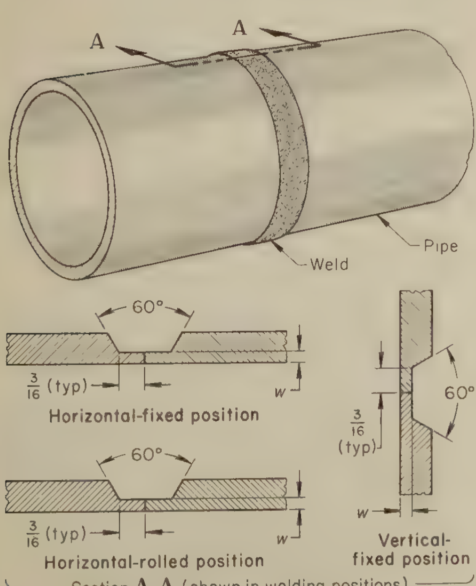
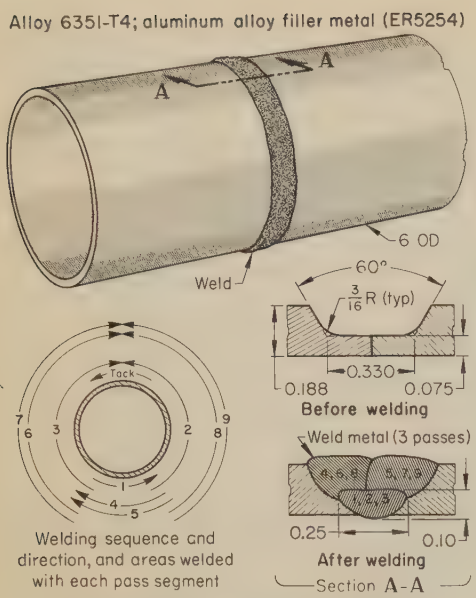


Fig. 38. Edge preparation for pipe welding using the conditions and root-face widths (w) given in Table 27

Table 27. Typical Conditions for Pipe Welding by the Manual Alternating-Current Gas Tungsten-Arc Process, Using Joint Designs Shown in Fig. 38

Nominal pipe size, in.	Wall thickness, in.	Root-face width (w in Fig. 38), in.	Electrode diameter, in.	Filler-metal diameter, in.	Gas-nozzle diameter, in.	Argon flow, cfh	Current (ac), amp	Number of passes
Horizontal-Fixed Position								
1	0.133	1/16	⅛	3/32	½	30 to 80	90	3 to 4
1¼	0.140	1/16	⅛	⅛	½	30 to 80	100	3 to 4
1½	0.145	1/16	⅛	⅛	½	30 to 80	110	3 to 4
2	0.154	1/16	⅛	⅛	½	30 to 80	120	3 to 4
2½	0.203	1/16	⅛	⅛	½	30 to 80	130	3 to 4
3	0.216	3/32	⅛	⅛	½	30 to 80	145	3 to 4
3½	0.226	3/32	⅛	⅛	½	30 to 80	150	3 to 4
4	0.237	3/32	3/16	⅛ to 5/32	½	35 to 80	160	3 to 4
5	0.258	3/32	3/16	5/32 to 3/16	½	35 to 80	180	3 to 4
6	0.280	3/32	3/16	5/32 to 3/16	½	50 to 80	195	3 to 4
8	0.322	3/32	3/16	5/32 to 3/16	½	50 to 80	210	3 to 4
10	0.365	3/32	3/16	5/32 to 3/16	½	50 to 80	230	3 to 4
12	0.406	3/32	3/16	5/32 to 3/16	½	50 to 80	245	3 to 4
Vertical-Fixed Position								
1	0.133	1/16	⅛	3/32	½	25 to 50	90	3 to 4
1¼	0.140	1/16	⅛	⅛	½	25 to 50	100	3 to 4
1½	0.145	1/16	⅛	⅛	½	25 to 50	110	3 to 4
2	0.154	1/16	⅛	⅛	½	30 to 60	120	4 to 5
2½	0.203	1/16	⅛	⅛	½	30 to 60	130	4 to 5
3	0.216	3/32	⅛	⅛	½	40 to 60	145	4 to 5
3½	0.226	3/32	⅛	⅛	½	40 to 60	150	4 to 5
4	0.237	3/32	3/16	⅛	½	40 to 60	160	4 to 5
5	0.258	3/32	3/16	5/32 to 3/16	½	50 to 60	180	4 to 5
6	0.280	3/32	3/16	5/32 to 3/16	½	50 to 60	195	5 to 6
8	0.322	3/32	3/16	5/32 to 3/16	½	60 to 80	210	5 to 6
10	0.365	3/32	3/16	5/32 to 3/16	½	60 to 80	230	5 to 6
12	0.406	3/32	3/16	5/32 to 3/16	½	70 to 80	240	5 to 6
Horizontal-Rolled Position								
1	0.133	1/16	⅛	3/32	7/16	25 to 40	90	1 to 2
1¼	0.140	1/16	⅛	⅛	7/16	25 to 40	100	1 to 2
1½	0.145	1/16	⅛	⅛	7/16	25 to 40	110	1 to 2
2	0.154	1/16	⅛	⅛	7/16	25 to 40	120	3 to 4
2½	0.203	1/16	⅛	⅛	7/16	30 to 40	130	3 to 4
3	0.216	3/32	⅛	⅛	½	30 to 40	145	3 to 4
3½	0.226	3/32	⅛	⅛	½	30 to 40	150	3 to 4
4	0.237	3/32	3/16	⅛	½	30 to 40	160	3 to 4
5	0.258	3/32	3/16	5/32	½	30 to 40	180	3 to 4
6	0.280	3/32	3/16	5/32 to 3/16	½	35 to 40	195	3 to 5
8	0.322	3/32	3/16	5/32 to 3/16	½	35 to 40	210	3 to 5
10	0.365	3/32	3/16	5/32 to 3/16	½	35 to 40	230	3 to 5
12	0.406	3/32	3/16	5/32 to 3/16	½	35 to 40	245	3 to 5



Manual AC Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Single-U groove
Joint spacing	None
Welding position	Horizontal-fixed pipe
Power supply	400-amp engine-driven generator
Fixtures	External alignment clamp
Torch	Water cooled
Electrode	3/16-in.-diam EWZr, taper ground
Filler-metal wire	1/8-in.-diam alloy ER5254(a)
Shielding gas	Argon, at 25 cfh
Current	190 amp, ac
Arc time per joint	7 min
Number of passes	Three
Hourly production per welder(b)	5 joints

(a) Chosen because it is compatible with all common aluminum alloys used for pipe and pipe fittings, ER5254 is a former AWS classification that has been replaced by ER5654. (b) Includes allowance for downtime.

Fig. 39. Welding large-diameter aluminum pipe for a pipeline (Example 312)

The can, welding fixture, clamping plates, stripping fixture, and joints are shown in Fig. 35. The inside radii of the welded corners were established by the corner radii of the fixture. The outside radii were dressed as needed to maintain a 0.04-in. maximum radius.

Tack welding before final welding is helpful in controlling distortion. Tack welds should be of ample size and strength, and preferably should be chipped out or tapered at the ends before welding over them. Alternating-current gas tungsten-arc welding is less suitable for tack welding than straight-polarity direct-current gas tungsten-arc welding, or than gas metal-arc welding (in which reverse-polarity direct current is used). Gas metal-arc welding (with dcrp) was used for tack welding during assembly of fuel tanks as described in Example 305; for final welding of the joints in these tanks, as described in the example that follows, manual alternating-current gas tungsten-arc welding was selected, because of the high weld quality that could be obtained with this process.

Example 311. Manual AC Gas Tungsten-Arc Welding of Fuel Tanks (Fig. 36)

Manual gas tungsten-arc welding, with alternating current, was used for making the 200 ft of groove welds and fillet welds required in the fabrication of the aluminum alloy fuel-storage tank shown in Fig. 36. The various butt, T and corner joints involved in welding the final assembly are also shown in Fig. 36. It was essential that the fuel tanks be leaktight, so the gas tungsten-arc process was selected for making these final welds because the ease with which the weld puddle could be controlled helped to ensure high weld quality.

The special preweld cleaning required for the components of this tank is described in Example 293. Tack welding of the components into 50 subassemblies, and tack welding of the subassemblies for final welding, were done by gas metal-arc welding, as described in Example 305, because the faster welding speed of that process reduced distortion and cost.

Before gas tungsten-arc welding, the tack welds and joints were mechanically cleaned with a stainless steel wire power brush. To avoid accumulation of dirt on the cleaned surfaces, final welding was done within 24 hr of the wire brushing.

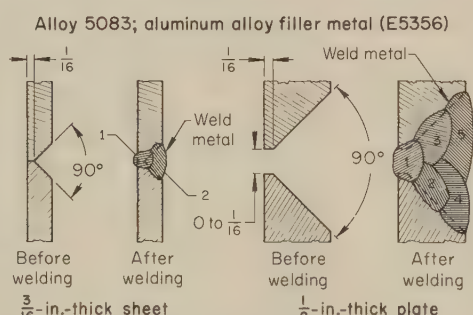
Alloy 5086-H32 sheet, 1/8 in. thick, was welded to itself and to 5083-H112 extrusions, which served as stiffeners and attachment flanges, and also formed an integral part of the fuel-tank wall. Bosses and fittings were of alloy 6061-T6. The parts were assembled and welded in a fixture.

As shown in the table that accompanies Fig. 36, many of the welding conditions were the same for all joints. Current varied according to joint design and welding position. Complete-penetration welds were deposited in single continuous passes. Tack welds were not removed. When the operator encountered a tack weld, he proceeded at about the same speed but added only enough filler metal to maintain proper weld contour. This procedure completely re-fused the tack welds.

After welding, the fixtured assembly was stress relieved in a furnace at 450 F for 2 hr, furnace cooled to 200 F, and then cooled in air to room temperature while still in the fixture.

Testing Procedures. Weld quality was checked by visual inspection based on workmanship samples, and the fuel tanks were tested for leaktightness by two different tests. In one test, the openings were plugged, the tanks were internally pressurized to 3 psi, and a liquid soap solution was flowed over all the welds. Leaks showed as a stream of fine bubbles. In the second test, the tanks were filled to 75% of capacity with a 0.25-to-0.50% aqueous solution of a detergent and a water-soluble dye, the remaining air space was pressurized to 3 psi, and the tanks were placed in a fixture and spun at 3 rpm for 3 min and 10 rpm for 7 min. The tanks were required to pass both tests with no leaks. If a leak occurred, which was unusual, repair was made by gas tungsten-arc welding.

Cleanness of Filler-Metal Wire. Because cleanness of the materials used to make the fuel tanks was of utmost importance (see Example 293), quality control of the filler-metal wire was necessary. In addition to the requirement that the wire meet Federal Specification QQ-R-566, samples of wire were tested periodically for cleanness by the following procedure. Using gas tungsten-arc equipment and settings (see the table that accompanies Fig. 36), an arc was struck near one edge of a clean coupon of alloy 5086 (1/8 in. thick by 4 in. wide by 6 in. long). Without adding filler metal, the arc was moved across the coupon, fusing well into it. If all conditions were correct, the weld puddle was clean and quiet. Next, some suspect filler metal was added to the puddle. Clean filler metal caused only a slight agitation of the puddle when added, and no dirt was seen floating on the molten puddle or on the weld bead afterward. Dirty filler metal caused violent action of the puddle and resulted in dirt floating on the surface. This was seen during the test through the proper shade of filter lens. After the test was completed, dirt could be seen on the surface of the weld bead.



Manual AC Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Single-V groove
Welding position	Horizontal
Power supply	Stabilized
Weld backing	None
Torch	Manual, water cooled
Electrode:	
3/16-in. sheet	1/8-in.-diam EWZr
1/2-in. plate	1/4-in.-diam EWZr
Filler metal:	
3/16-in. sheet	5/32-in.-diam ER5356
1/2-in. plate	3/16-in.-diam ER5356
Shielding gas	Argon, at 35 cfh
Current:	
3/16-in. sheet	160 amp, ac
1/2-in. plate	300 amp, ac
Preheat:	
3/16-in. sheet	None
1/2-in. plate	200 F
Interpass temperature	200 to 400 F
Number of passes:	
3/16-in. sheet	Two
1/2-in. plate	Five

Results of Qualification Tests

Tensile strength	26,805; 27,400 psi(a)
Failure	Ductile failure, in weld metal
Guided bend tests (4)	Results acceptable

(a) Results of two tests in reduced-section tensile specimens 0.750 by 0.487 in. and 0.751 by 0.474 in.

Fig. 40. Welds in 3/16-in. sheet and 1/2-in. plate, made in the horizontal position by the gas tungsten-arc process (Example 313)

Because gas tungsten-arc welding with alternating current affords close control of the weld puddle in all positions, it is often used for the welding of pipe joints. Typical welding conditions are given in Tables 26 and 27, and joint edge preparations are shown in Fig. 37 and 38.

Manual alternating-current gas tungsten-arc welding is an economical process for joining pipe up to fairly long lengths. The equipment required is less expensive than that for gas metal-arc welding and it needs less maintenance, a desirable feature when field welding. The suitability of this process for welding aluminum pipe is described in the following example, in which the importance of joint design is also discussed.

Example 312. Welding Pipe in the Horizontal-Fixed Position by the Gas Tungsten-Arc Process (Fig. 39)

The 6-in.-OD, 0.188-in.-wall alloy 6351-T4 pipe shown in Fig. 39 was welded economically in lengths up to five miles (for use in a pipeline) by the manual gas tungsten-arc process. Because the pipe was fixed in the horizontal position, it was necessary to be able to control the weld puddle in all positions. The gas tungsten-arc process was therefore chosen. The joint was a single-U-groove butt with no root opening, as shown in Fig. 39. Joint surfaces were precleaned by wiping with solvent, an external clamp was used to align the joint, and the joint was tack welded. After tack welding, the clamp was removed and the joint was welded in three passes, each consisting of three segments. By remelting starts and stops of each segment when restriking the arc, potential defects were avoid-

ed. The weld passes are shown in section A-A in Fig. 39, and the sequence and direction of the segments of each weld pass are shown at lower left in Fig. 39. Segments 1, 4 and 5 were made in the overhead position, with the welder lying under the pipe, and the remainder of the segments were made in the vertical-up position, with the welder kneeling. Welding conditions are given in the table that accompanies Fig. 39.

Preheating parts thicker than about 3⁄16 in. may be advantageous when gas tungsten-arc welding with alternating current. The preheating temperature depends on the thickness of the base metal and the particular problems associated with the job. Often 200 F is a sufficient preheat temperature for material up to ½ in. thick, as in the following example, in which the use of preheat and careful selection of electrode material helped in obtaining the necessary mechanical properties.

Example 313. Use of Preheat in Welding ½-In.-Thick Alloy 5083 Plate (Fig. 40)

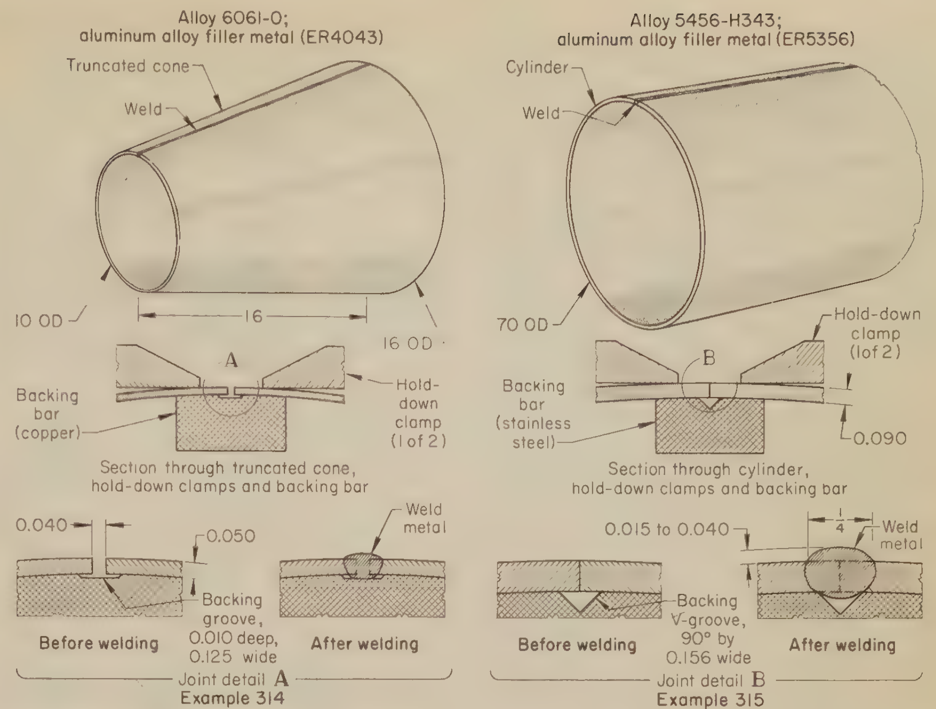
Figure 40 shows the joint designs and the buildup sequences used in manual gas tungsten-arc welding of 3⁄16-in.-thick sheet and ½-in.-thick plate, both of alloy 5083. In welding the ½-in. plate, preheating to 200 F was found helpful in producing a weld puddle fluid enough for welding in the horizontal position; the 3⁄16-in. sheet could be welded without preheat. Both the sheet and the plate were welded with EWZr electrodes, which resulted in clean weld metal, with minimum tungsten contamination.

The edges to be welded were grooved by machining or grinding, or both. All grease, oil, and oxide were removed by solvent cleaning and brushing with a stainless steel wire brush before welding. It was essential that the welding current and method of depositing the weld metal be such that there was no undercutting. All cracks and blowholes that appeared on the surface of a bead were removed by chipping or grinding before depositing the next bead. Production data and results of welding-procedure qualification tests are summarized in the table that accompanies Fig. 40.

Automatic Welding. The gas tungsten-arc process can be mechanized either with or without the addition of filler metal. If filler metal is used, it is normally added mechanically by cold-wire feed units. Automatic gas tungsten-arc welding usually employs a shorter arc length, and higher welding current and welding speed, and results in deeper penetration than manual welding. Typical conditions for the automatic alternating-current gas tungsten-arc process, for butt joints and metal thicknesses from 1⁄16 to ½ in., are given in Table 28.

Joint fit-up, joint cleanness and filler-metal cleanness are especially important with automatic welding. Joint-edge cleaning must be thorough and should immediately precede welding. Additional torches can be installed ahead of the main welding torch for cleaning and preheating.

Automatic alternating-current gas tungsten-arc welding has been used in the aerospace industry for joining relatively thin aluminum. High-strength high-quality welds can be made without excessive distortion, and the quantities are usually large enough to warrant mechanization. Two such applications of the automatic gas tungsten-arc process are described in Examples 314 and 315, which follow.



Item	Example 314 (Truncated cone)	Example 315 (Cylinder)
Conditions for Automatic AC Gas Tungsten-Arc Welding		
Base metal	6061-O	5456-H343
Base-metal thickness, in.	0.050	0.090
Joint type	Butt	Butt
Weld type	Square groove	Square groove
Root opening, in.	0.040	None
Welding position	Flat	Flat
Power supply	300 amp with high-frequency stabilization	300 amp with balanced wave
Mechanization and fixtures	Automatic welding machine with segmented hold-down fingers	
Backing	Copper bar	Stainless steel bar
Torch	Water cooled	Water cooled
Electrode	⅛-in.-diam EWP	5⁄32-in.-diam EWP
Filler metal	1⁄16-in.-diam ER4043	0.045-in.-diam ER5356
Shielding gas	Argon, at 16 cfh	Argon, at 22 cfh
Current (ac), amp	100	185
Voltage, v	40	10 to 11
Filler-metal feed, ipm	22	112
Welding speed, ipm	24	21
Number of passes	One	One

Fig. 41. A truncated cone and a cylinder that were automatic gas tungsten-arc welded, and hold-down devices, backing-groove designs, and joint details (Examples 314 and 315)

Examples 314 and 315. Welding Aerospace Parts by the Automatic Alternating-Current Gas Tungsten-Arc Process (Fig. 41)

Example 314 — Truncated Cone (Fig. 41). Because the welded truncated cone (alloy 6061-O) shown at the left in Fig. 41 served as a blank to be explosively formed into a streamlined (ballistic ogive) shape, the welded joint had to be ductile enough to undergo considerable distortion without rupturing. The 0.010-in. by 0.125-in. groove in the backing bar provided for complete joint penetration, but with limited reinforcement to help ensure ductility of the weld. After welding, but before forming, the weld bead was roll planished. After forming, welds were checked for cracks by liquid-penetrant inspection. The joints made using the conditions listed in the table that accompanies Fig. 41 consistently had acceptable ductility, and they were crack-free after forming.

Example 315 — Cylinder (Fig. 41). The alloy 5456-H343 cylinder shown at the right in Fig. 41 was part of a missile fuel tank. The 0.156-in.-wide 90° V-groove in the backing bar was used to provide the maximum root reinforcement allowed. The weld bead face was ¼ in. wide and had a reinforcement of about 30%. Welding was done under the conditions given in the table that accompanies Fig. 41. The square-groove butt joint had zero root opening. The edges were drawfiled and scraped to remove surface oxides prior to welding.

Welds had acceptable radiographic quality and tensile properties — 31,820 psi yield strength, 50,620 psi tensile strength, and 5.5% elongation. Gas metal-arc welding was also tried for this part, and although welding speed was about twice that for gas tungsten-arc welding, rejections because of cracks and porosity were numerous.

Another application in which automatic alternating-current gas tungsten-arc welding was used to join rela-

Table 28. Typical Conditions for Automatic Gas Tungsten-Arc Welding of Butt Joints, Using Alternating Current (a)

Metal thickness, in.	Electrode diameter, in.(b)	Argon flow, cfh	Welding current (ac), amp(c)	Number of passes
1⁄16	1⁄16	15	60 to 80	1
⅛	3⁄32	20	125 to 145	1
3⁄16	⅛	20	190 to 220	1
¼	3⁄16	25	260 to 300	2
⅜	¼	30	330 to 380	2
½	¼	30	400 to 450	4

(a) Power supply: alternating current with superimposed high-frequency current, balanced wave. (b) Unalloyed tungsten electrodes are recommended. (c) Current ranges are averages for butt welds with square edges. For metal ¼ in. thick or more, edges are usually beveled.

tively thin aluminum was the fillet welding of an 0.087-in.-thick alloy 5456-H343 extruded T-ring stiffener to the inside surface of a 0.071-in.-thick alloy 5456-H343 sheet cylinder, as shown in Fig. 42. The fillet welds were made using an oscillating torch, which was mounted on a boom that reached inside the cylinder. Welding was done in the horizontal-rolled position, with the cylinder being rotated by a precision positioner. The torch had arc-voltage control. A 300-amp balanced-wave power supply and 0.030-in.-diam ER5556 filler-metal wire were used.

The assembly was part of a fuel tank. Manual welding of the stiffeners had been tried, but it resulted in excessive distortion, defects requiring repair, and excessive production time. Automatic welding reduced the number of out-of-tolerance parts by 90%, weld defects by 30%, and welding time per tank by 200 man-hours.

As the thickness of the metal to be welded increases, power requirements increase. When the power requirement exceeds the capacity of the power supply, maximum welding speed cannot be attained and one of the advantages of mechanization is not realized. For single-pass square-groove butt welding, the advantage of higher welding speed is lost when the thickness of the material reaches 3/16 to 1/4 in. For example, when welding the circumferential seam of a manifold sump in 0.190-in.-thick alloy 5052-H32, the current was raised from 210 amp, which is normally used for automatic gas tungsten-arc welding of this thickness of aluminum, to 310 amp (the upper limit of the power supply) and the welding speed was raised to only 8 in. per minute, about the same as for manual welding. The weld joint and the conditions for welding are shown in Fig. 43. The filler metal was smaller in diameter than often used, to improve control of the weld puddle. Although the welding speed was slow, the welds did meet requirements — namely, uniform bead width, very smooth bead surface, radiographic quality to class II (MIL-R-45774), and weld-metal yield strength of 14,150 psi, tensile strength of 29,300 psi, and elongation of 14%.

For butt welds in material thicker than 3/16 to 1/4 in., the edges of the joint are usually beveled to a single or double V-groove for multiple-pass welding. An alternative process would be gas tungsten-arc welding with straight-polarity direct current, which can make square-groove welds in material up to 3/4 in. thick without difficulty.

Repair welding can be done by the alternating-current gas tungsten-arc process. In the following example, filler metal was not added until a clean weld puddle was well established, which was helpful in obtaining clean weld metal on a resin-impregnated casting.

Example 316. Repair of Spotfacing Error in Resin-Impregnated Aluminum Alloy Casting (Fig. 44)

A spotfacing error in an attachment boss (Fig. 44) used for bolting together the two halves of an aircraft-engine crankcase casting made of alloy 355-T7 reduced the height of a boss below tolerance. The casting was salvaged by weld repair, which was permitted because the service load in the boss area was relatively low. The equipment and welding conditions, as listed in the table that accompanies Fig. 44, were conventional for gas tungsten-arc welding. However, deposition of the weld bead required careful manipulation to avoid development of porosity and to obtain complete fusion, because the casting had been impregnated with a polyester resin.

The casting had been cleaned by blasting at the foundry, but required vapor degreasing and stainless steel wire brushing of the boss and surrounding area. Preheat and postheat were considered unnecessary because the service load was not a critical factor in this portion of the casting.

To remove the impregnated resin, an arc was struck and manipulated over a small area until a puddle of clean metal was obtained. This puddle was then extended to cover the entire area to be welded; no filler metal was used at this stage. After the puddle solidified, the area was wire brushed. The arc was restruck and a thin layer of filler metal was deposited in crescent-shape beads to cover the area. This layer was wire brushed, and a second bead was similarly deposited, bringing the buildup to a height sufficient for re-spotfacing to correct size.

After visual inspection and machining, the welded area was radiographed to check for cracks and porosity. The repair operation proved satisfactory.

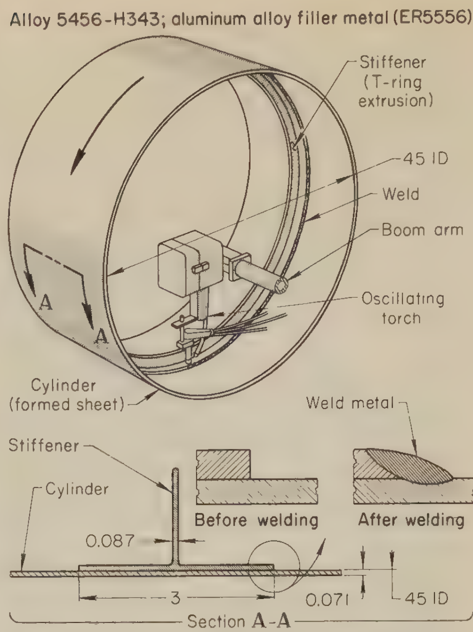
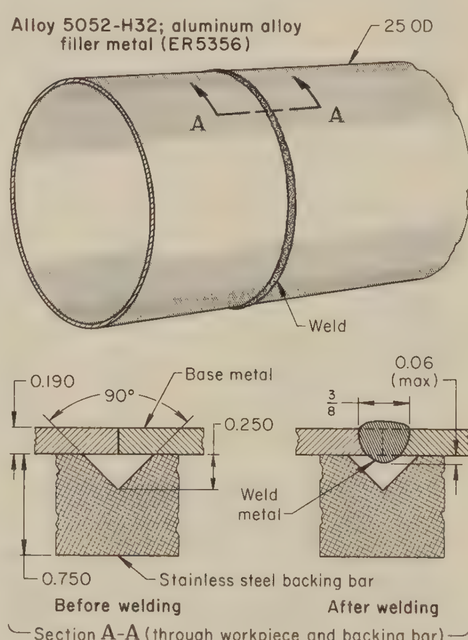


Fig. 42. Automatic ac gas tungsten-arc welding, with an oscillating torch, of an extruded stiffener to a fuel-tank cylinder, which was rotated in a precision positioner during welding



Automatic AC Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Square groove
Root opening	None
Welding position	Horizontal-rolled pipe
Power supply	300 amp, balanced wave
Fixtures	Clamps, stainless steel backing bar(a), rotating positioner
Torch	Water cooled
Electrode	3/16-in.-diam EWP
Filler metal	0.045-in.-diam ER5356
Shielding gas	Argon, at 20 cfh
Current	310 amp, ac
Voltage	11 to 12 v
Filler-metal feed	88 ipm
Welding speed	8 ipm
Number of passes	One

(a) The segmented backing bar (25 in. in diameter, with a 90° V-groove 0.250 in. deep) was hydraulically expanded to align the joint edges against an external clamping fixture.

Fig. 43. Square-groove butt weld that represents practical thickness limit for automatic alternating-current gas tungsten-arc welding in one pass

Reverse-Polarity Direct-Current Gas Tungsten-Arc Welding

Although gas tungsten-arc welding of aluminum with reverse-polarity direct current (electrode positive) is seldom used, this process offers certain advantages in the joining or repairing of thin-wall heat exchangers, tubing and similar assemblies with sections up to about 3/32 in. thick.

The process is characterized by shallow penetration, ease of arc control and good arc cleaning action. However, reverse-polarity direct current causes most of the heat of the arc to be generated at the electrode, which necessitates the use of large-diameter electrodes and decreases arc efficiency. If practical electrode sizes are to be used, work must be thin. For example, a 1/4-in.-diam electrode is needed in order to carry a 125-amp current. This would weld aluminum up to about 1/8 in. thick.

Reverse-polarity direct-current welding is useful for small shops because it can be used with almost any general-purpose power supply. Thoriated tungsten electrodes are normally used, and argon shielding is preferred, because it facilitates arc starting and arc control. Table 29 gives typical conditions for welding butt joints in metal up to 0.050 in. thick with reverse-polarity direct current.

Reverse-polarity direct-current welding was used in constructing from 0.020-in.-thick alloy 1100 sheet reflectors that required a high-quality mirror finish after buffing. Riveting could not be used as it resulted in distortion and polishing difficulties. Spot and seam resistance welding were ruled out by the shape of the parts, and the material was too thin to be joined by gas metal-arc welding. Therefore, gas tungsten-arc welding had to be used, and reverse-polarity direct current was selected because its shallow penetration reduced the risk of burn-through.

The reflectors weighed about 1 lb each and required butt, corner and lap

joints. The joint areas were precleaned by sandblasting, and the parts were lightly clamped and tack welded.

Direct current was supplied by a rectifier of 200-amp capacity, adjustable to as low as 10 amp. A standard water-cooled torch was used, with a ceramic gas nozzle, argon shielding gas, a 3/16-in.-diam thoriated tungsten electrode, and ER1100 filler metal. Reflectors of satisfactory quality were made without difficulty.

Reverse-polarity direct current was also used in welding an open box to be used as a housing. The housing was required to be both rigid and lightweight. Sand casting could not be used because the walls were too thin, and the design and the low total production ruled out die casting. Therefore, the housing was designed as a weldment in 0.050-in.-thick alloy 6061-T6 sheet, with stiffeners and numerous bosses, up to 1/4 in. thick, welded on. The housing weighed about 3 lb.

Resistance spot welding of the housing joints was unsuitable because of the shape of the components and the combination of thin and thick sections. Gas metal-arc welding was ruled out because of the short joint lengths, the need for frequent repositioning of the assembly, and the thinness of the metal. Therefore, gas tungsten-arc welding was used and reverse-polarity direct current was selected because of its shallow penetration.

The parts were vapor degreased, and tack welded in standard clamps. They were then removed from the clamps and were welded without preheating. The current was supplied by a 200-amp rectifier. A special foot switch was used to break the arc at the end of the seam, to prevent the formation of craters. A standard water-cooled torch was used, with a ceramic gas nozzle, argon shielding, a 3/32-in.-diam thoriated tungsten electrode, and ER4043 filler metal. After welding, the housing was re-aged, which gave it sufficient rigidity and dimensional stability, and critical dimensions were machined.

Straight-Polarity Direct-Current Gas Tungsten-Arc Welding

With straight-polarity direct current (electrode negative), the heat is generated at the workpiece surface, producing deep penetration and permitting higher welding currents for a given electrode size than can be used with reverse polarity. As a result, smaller electrodes can be employed with a given welding current, which helps to keep the weld bead narrow. Because of the narrow and deep penetration obtained, less edge preparation and less filler metal are needed, and welding is faster than when using reverse polarity. Because of the high heat generated on the workpiece surface, melting is rapid, no preheat is required, even of thick sections, and there is little distortion of the base metal.

The process has been used for years on as-received material to make irrigation tubing in high-speed tube mills, at speeds up to 50 ft per minute. It is the process employed in almost all of the highly automatic coil-joining welders used on continuous process lines in the aluminum industry. Perhaps more lineal feet of welds in aluminum alloys have been made by this process than by any other process.

Table 29. Typical Conditions for Manual Gas Tungsten-Arc Welding of Square-Groove Butt Joints, Using Reverse-Polarity Direct Current (a)

Metal thickness, in.	Electrode diameter, in. (b)	Filler-metal diameter, in.	Argon flow rate, cfh	Current (dcrp), amp (c)
0.020	1/8 to 5/32	0.020	15-20	40-55
0.030	3/16	0.020 or 3/64	15-20	50-65
0.040	3/16	3/64	25-30	60-80
0.050	3/16	3/64 or 1/16	25-30	70-90

(a) Single-pass welds made in the flat position. Use of a backing bar having a generous groove is recommended. (b) Thoriated tungsten electrodes. (c) Higher currents with larger electrodes may be used for automatic welding.

Straight-polarity direct-current gas tungsten-arc welding is also especially suitable for joining thick sections and has been used on aluminum up to 1 in. thick. It is well suited for tack welding and produces welds of good contour and high quality. Butt joints are characteristically narrow and flat, and buildup can be controlled by varying the size and amount of filler wire. Fillet welds characteristically have a concave or flat face. Fillet size can be regulated easily by varying the size of the filler wire. The shape of the weld is generally uniform, and the concentrated heat of the arc gives good fusion at the root of the joint.

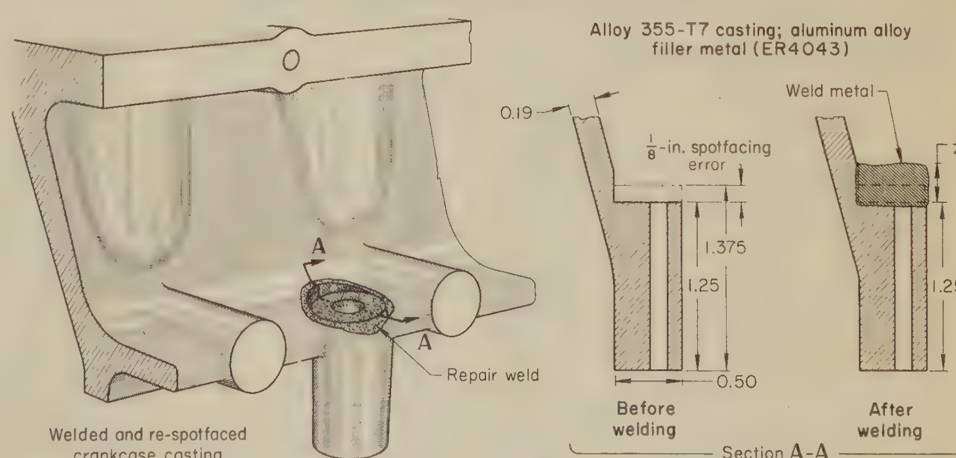
The mechanical properties of welds made by this method are equal to or better than those made with alternating current. The welding heat is more

Table 30. Typical Conditions for Manual Gas Tungsten-Arc Welding of Butt Joints, Using Straight-Polarity Direct Current, Thoriated Tungsten Electrodes, and Helium Shielding

Metal thickness, in.	Groove design	Electrode diameter, in.	Filler-metal diameter, in.	Helium flow rate, cfh	Current (dcsp), amp	Voltage, v	Welding speed, ipm	Number of passes
0.030	Square	0.040	3/64	20	20	21	17	1
0.040	Square	0.040	1/16	20	26	20	16	1
0.060	Square	0.040	1/16	20	44	20	20	1
0.090	Square	1/16	3/32	30	80	17	11	1
0.125	Square	1/16	1/8	20	118	15	16	1
0.250	Square	1/8	5/32	30	250	14	7	1
0.500	90° single V, 1/4-in. root face	1/8	5/32	40	310	14	5½	2
0.750	90° double V, 3/16-in. root face	1/8	5/32	50	300	17	4	2
1.000	90° double V	1/8	1/4	50	360	19	1½	5

Table 31. Typical Conditions for Manual Gas Tungsten-Arc Welding of T and Lap Joints, Using Straight-Polarity Direct Current, Thoriated Tungsten Electrodes, and Helium Shielding

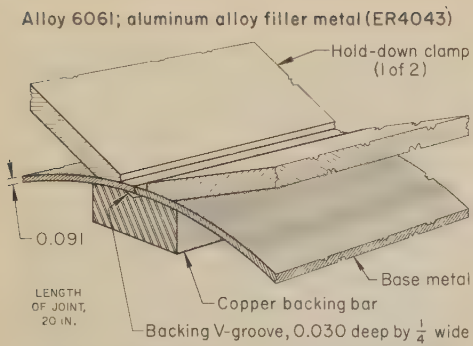
Metal thickness, in.	Welding position	Fillet size, in.	Electrode diameter, in.	Filler-metal diameter, in.	Helium flow rate (1/2-in. nozzle), cfh	Current (dcsp), amp	Voltage, v	Welding speed, ipm
0.090	Horizontal	1/8	3/32	3/32	40	130	14	21
0.125	Horizontal	1/8	3/32	3/32	40	180	14	18
0.250	Horizontal	3/16	1/8	5/32	40	255	14	15
	Vertical	3/16	1/8	5/32	40	230	14	10
0.375	Horizontal	5/16	1/8	1/4	50	290	14	7
	Horizontal	3/16	1/8	5/32	50	335	14	14
0.500	Horizontal	5/16	1/8	1/4	50	315	16	7
	Vertical	5/16	1/8	1/4	50	315	16	6



Conditions for Manual AC Gas Tungsten-Arc Repair Welding

Weld type .... Surfacing	Torch .... 300 amp, water cooled
Welding position .... Flat	Gas nozzle .... 1/2-in. diam, ceramic
Power supply .. 40-v, 300-amp transformer, with high-frequency oscillator, 60% duty cycle	Electrode .... 1/8-in.-diam EWP
Special equipment .... Foot control for frequency, current, and delayed start and shutoff of gas and water; automatic voltage regulation	Filler metal 3/32-in.-diam ER4043
	Shielding gas ...... Argon, at 25 cfh (flowmeter control)
	Current .... 150 amp, ac (foot control for 40 to 150 amp)
	Voltage .... Automatically regulated

Fig. 44. Portion of an aircraft-engine crankcase casting, showing repair weld (Example 316)



Automatic Gas Tungsten-Arc Welding (dcsp)

Joint type	Butt
Weld type	Square groove
Power supply	200 amp, with drooping output
Mechanization	Cold wire feeder; torch mounted on a carriage
Fixtures	Hold-down clamps; grooved copper backing bar
Torch	Water cooled
Electrode	3/32-in.-diam EWP
Filler metal	1/16-in.-diam ER4043
Shielding gas	Helium, at 50 cfh; argon, at 5 cfh
Current	200 amp, dcsp
Filler-metal feed	50 ipm
Welding speed	25 ipm
Number of passes	One

Fig. 45. Arrangement for gas tungsten-arc welding a 20-in.-long longitudinal joint in a cylinder, showing hold-down clamps and grooved backing bar (Example 317)

concentrated, the heat-affected zone is smaller and, because preheating is not needed and only a few weld passes are customary, residual tensile stress is low. Also, cold worked alloys retain their temper. These are important advantages when joining heavy sections of alloys such as the 5*xxx* series.

As surface oxides on aluminum are not removed during straight-polarity direct-current welding, thorough preweld cleaning is necessary to ensure that oxide will not be trapped in the molten weld puddle. Normal practice in the aerospace industry is to clean chemically and to scrape or file the joint area. However, many commercially acceptable welds have been made with no preweld cleaning.

The surfaces of the welds are not as bright as those made with alternating current because they are coated with an oxide film. The film does not indicate any lack of fusion or the presence of porosity or inclusions and is easily removed by a light wire brushing.

Because of the highly penetrating nature of the straight-polarity direct-current arc, melting occurs the instant the arc is struck. Care should be taken to strike the arc within the weld area to prevent undesirable marking of the workpiece. Although a high-frequency sparking current is not required to stabilize the arc during direct-current welding, it is useful for starting the arc without marking the workpiece or causing tungsten inclusions. A starting tab of scrap aluminum can be used for touch starting if a high-frequency circuit is not available.

Because continuous high-frequency and wave-balancing circuits are not used in direct-current welding, performance can be duplicated easily by using standardized arc voltages and amperages, even on different machines. Normally, thoriated tungsten electrodes are employed, with helium shielding.

Manual Welding. Typical conditions for welding by the manual straight-polarity direct-current gas tungsten-arc process are given in Tables 30 and 31. Metal thicker than 1/4 in. is grooved (single-V or single-U) to ensure complete joint penetration. A double-V or double-U groove may be advantageous for metal more than 1/2 in. thick.

Table 32. Typical Conditions for Automatic Gas Tungsten-Arc Welding of Square-Groove Butt Joints, Using Straight-Polarity Direct Current (a)

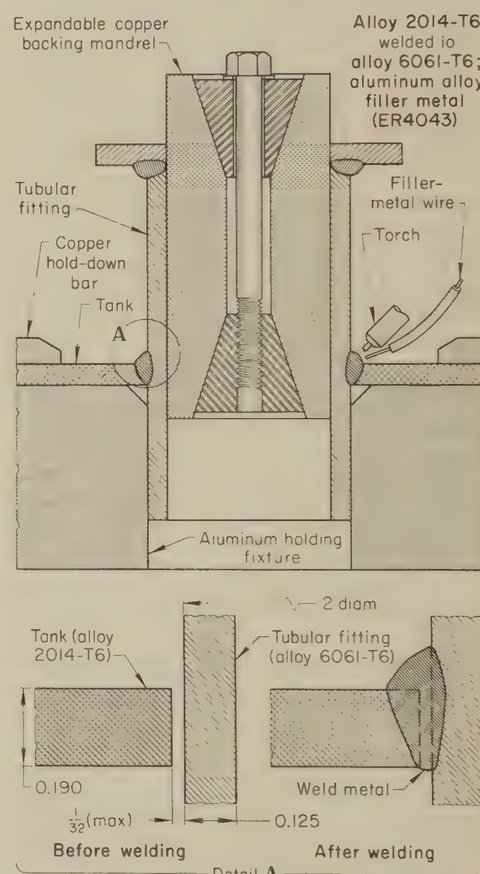
Metal thickness, in.	Electrode diameter, in. (b)	Filler metal: Diameter, in.	Filler metal: Feed, ipm	Helium flow rate, cfh	Arc: Current (dcsp), amp	Arc: Voltage, v	Welding speed, ipm
0.025	3/64	3/64	60	60	100	10	60
0.031	3/64	3/64	76	60	110	10	60
0.040	3/64	3/64	68	60	125	10	60
0.051	3/64	3/64	64	60	150	12	60
0.062	3/64	3/64	99	60	145	13	60
0.080	3/64	3/64	100	60	290	10	60
0.125	1/16	1/16	55	30	240	11	40
0.250	1/16	1/16	40	30	350	11	15
0.375	1/16	1/16	30	40	430	11	8

(a) Single-pass welds made in the flat position. (b) Thoriated tungsten electrodes.

Table 33. Typical Conditions for Automatic Gas Tungsten-Arc Welding of Square-Groove Butt Joints, Using Straight-Polarity Direct Current (a)

Metal thickness, in.	Welding position (b)	Filler-metal (1/16-in. diam) feed, ipm	Helium flow rate, cfh	Arc: Current (dcsp), amp	Arc: Voltage, v	Welding: Speed per pass, ipm	Welding: Number of passes
Alloy 5083							
1/4	F	30	100	250	11	25	Two, one each side
1/4	V	None	50	260	10	20	Two, one each side
3/8	F, V	None	80	300	12	14	Two, one each side
3/8	F	12	100	360	10	10	Two, one each side
1/2	F, V	None	100	400	10	15	Two, one each side
1/2	F	12	100	390	10	8	Two, one each side
3/4	F, V	None	100	500	9	5	Two, one each side
Alloy 2219							
1/4	F, V	36	100	145	12	8	Two, one side
1/4	H	36	100	135	12	10	Two, one side
3/8	F, V	32	120	220	12	8	Two, one side
3/8	H	32	120	180	12	10	Two, one side
1/2	H, V	10	100	250	12	8	Two, one each side
5/8	H, V	5-7	120	300	12	7	Two, one each side
3/4	H, V	5-7	125	340	12	6	Two, one each side
7/8	H, V	4-6	125	385	12	5	Two, one each side
1	H, V	3-5	120	425	12	4	Two, one each side
Alloy 7039							
1/4	F, V, H	None	100	265	10	18	Two, one each side
1/4	F	40	120	250	14	20	Two, one each side
3/8	F, V	None	50	300	10	12	Two, one each side
1/2	F, V	None	100	390	10	15	Two, one each side
3/4	F, V	None	100	450	9	6	Two, one each side
3/4	F	48	100	390	10.5	4	Two, one each side

(a) Thoriated tungsten electrodes: 1/8-in.-diam electrodes with 0.100-in.-diam tip for metal 1/4 to 3/4 in. thick; 5/32-in.-diam electrodes with 0.125-in.-diam tip for metal 7/8 in. thick; 3/16-in.-diam electrodes with 0.156-in.-diam tip for metal 1 in. thick. (b) F = flat; H = horizontal; V = vertical.



Semiautomatic Gas Tungsten-Arc Welding (dcsp)

Joint type	Circumferential T
Weld type	Fillet
Power supply	500 amp, with constant voltage and high-frequency start
Mechanization	Automatic torch rotation, automatic workpiece rotation
Fixtures	Expanding backing mandrel, copper hold-down bars, holding fixture
Torch	Mechanically held, pencil type, water cooled
Electrode	3/32-in.-diam EWTh-2
Filler metal	1/16-in.-diam ER4043
Shielding gas	Helium, at 75 cfh
Current	160 amp, dcsp
Voltage	15 v
Filler-wire feed	110 ipm
Welding speed	12 ipm

Fig. 46. Welding a tubular fitting into the wall of a tank (Example 318)

The welder must use care in maintaining a suitable short arc length. In addition to the standard techniques (runoff tabs and striking plates) for preventing and filling craters, foot-operated heat controls are used. These controls are also advantageous for adjusting the current as the workpiece heats up and as section thickness changes. The arc is moved steadily forward and filler metal is fed into the leading edge of the weld puddle or laid on the joint and melted by the arc. Bead size can be controlled by varying filler-metal size.

Automatic Welding. Straight-polarity gas tungsten-arc welding is readily adaptable to mechanization, which is desirable in order to maintain the required short arc lengths. The result is improved weld quality, as discussed in the following example, which describes the automatic butt welding of relatively thin alloy 6061 sheet.

Example 317. Welding 0.091-In.-Thick Sheet by the Automatic Straight-Polarity Direct-Current Gas Tungsten-Arc Process (Fig. 45)

A 20-in.-long butt weld (see Fig. 45) used to complete a cylinder formed from 0.091-in.-thick alloy 6061 sheet was required to be defect-free under radiographic inspection. Automatic gas tungsten-arc welding was chosen, a clamping fixture and a grooved copper backing bar were used, and the process variables were closely controlled (see the table that accompanies Fig. 45).

The joint was cleaned chemically and by draw filing. To facilitate arc initiation and adjustment, starting and runoff tabs were attached at the joint. The welding torch was adjusted to give a very short arc — from below the original workpiece surface to about 0.015 in. above, and on the verge of short circuiting. To ensure accurate weld placement, the carriage with the welding torch mounted on it was aligned with the joint to within ±0.005 in. for the entire 20-in. length of the weld. Helium with a small amount of argon added was the shielding gas.

Sound, defect-free welds were produced. Production rate varied from 20 to 40 pieces per shift (including cleaning and setup time), depending on operator skill.

Mechanization is useful in preventing crater cracking by eliminating all but one start and stop. This is illustrated in the following example, which describes the fillet welding of alloy 6061 tubing to alloy 2014 sheet.

Example 318. Semiautomatic Welding of 0.125-In.-Wall Tubular Fittings in a 0.190-In.-Thick Tank Wall (Fig. 46)

When manual gas tungsten-arc and gas metal-arc welding the alloy 6061 tubular fittings shown in Fig. 46 to alloy 2014 tank walls, several repositionings of the workpieces were required, necessitating several starts and stops. Weld crater cracking became a problem, and so it was decided to change to semiautomatic gas tungsten-arc welding, which could be done continuously and with close control. Straight-polarity direct current was selected because of the deep penetration that could be obtained by using it.

During welding, either the workpieces were rotated and the torch was stationary, or the torch was rotated and the workpieces were stationary — depending on workpiece size and the tooling available. Auxiliary wire feed was used to obtain the required fillet size. Some designs required fillet welds on both sides of the joint. Precise tooling was needed to align the electrode and the filler wire with the joint. Copper backing mandrels and copper hold-down bars promoted rapid cooling and faster welding. As a result, the size of the heat-affected zones was restricted and good weld strength was obtained.

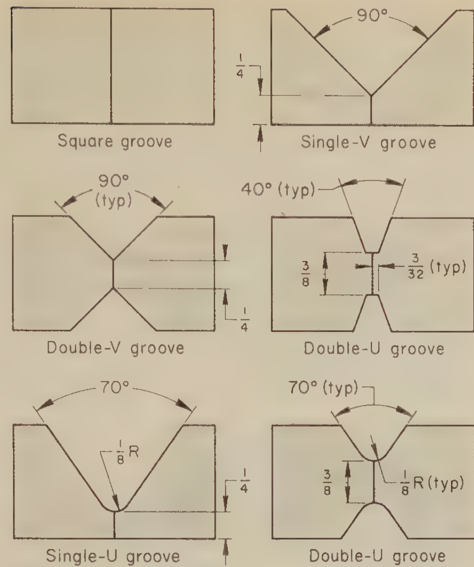


Fig. 47. Typical joint designs for making butt welds by the automatic straight-polarity direct-current gas tungsten-arc process

Various methods were used to minimize crater cracking, the preferred method being automatic sequencing of welding variables so as to add filler-metal wire after travel had stopped, while gradually increasing arc voltage and decreasing current.

Preweld cleaning consisted of manual brushing, wiping with commercial cleaners, and wiping dry with clean cloths. Welding conditions and equipment data are shown in the table that accompanies Fig. 46.

For best results, a fully mechanized automatic setup should be employed. With a fully automatic setup, welds are made in aluminum alloys from 0.010 in. thick to more than 1 in. thick. Because this process allows precise control of weld penetration, it is often selected for joining aluminum in the thickness range from 0.010 to ⅛ in.

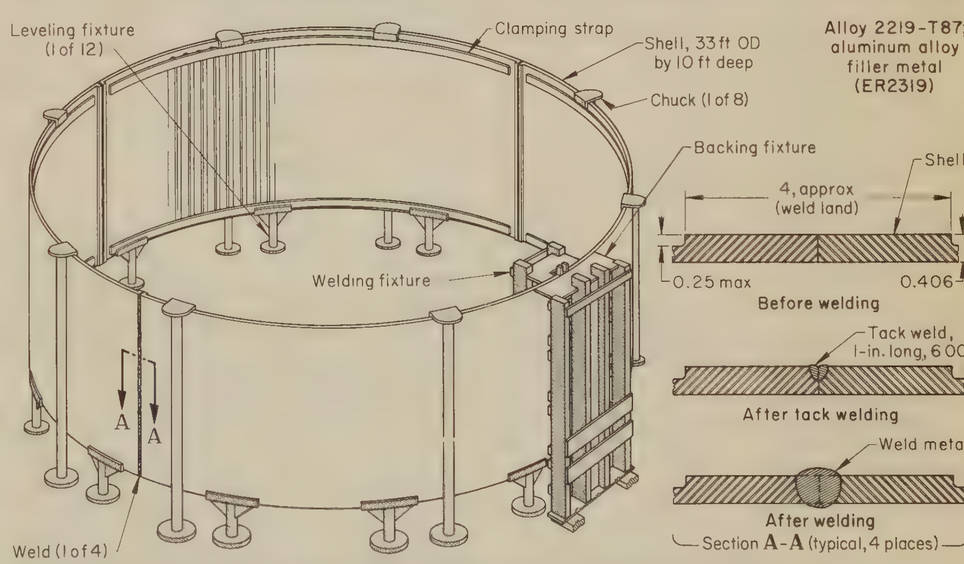
Typical conditions for making square-groove butt welds with automatic straight-polarity direct-current gas tungsten-arc welding in aluminum up to ⅜ in. thick are given in Table 32. Automatic welding has also been used to weld square-groove butt joints in aluminum up to 1¼ in. thick, but V-groove and U-groove edge preparations are often used on thick sections. Mechanical and magnetic oscillation can be used to spread the filler metal and to aid fusion when groove welding with this process. Typical edge preparations are shown in Fig. 47.

Because square-groove butt welding using the automatic straight-polarity direct-current gas tungsten-arc process results in narrow weld beads, low dilution with filler metal, and excellent weld strength, this process is used for joining rather thick sections of high-strength aluminum alloys. Conditions for welding three such alloys (5083, 2219 and 7039) are given in Table 33.

Two examples of this type of weld in 0.406-in.-thick and 1.000-in.-thick alloy 2219 plate follow.

Example 319. Making Aerospace-Quality Arc Welds in Alloy 2219 Plate (Fig. 48)

In producing the large cylindrical shell shown in Fig. 48 for part of a rocket-propellant tank, it was necessary to weld four segments together. Alloy 2219-T87 was cho-



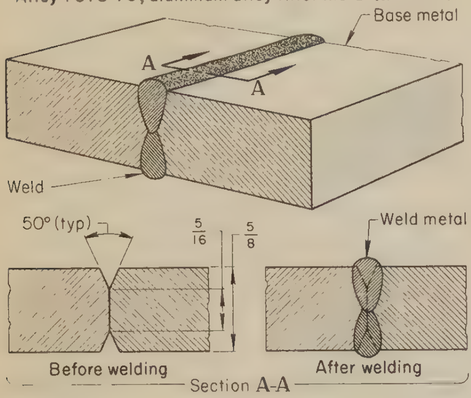
Conditions for Automatic Gas Tungsten-Arc Welding (dcsp)

Joint type	Butt	Gas nozzle	⅝-in. diam, copper
Weld type	Square groove	Electrode	⅛-in.-diam EWTh-2, with tip taper ground to 0.090-in. diam
Root opening	None	Filler metal	$\frac{1}{16}$-in.-diam ER2319
Welding position	Vertical up	Shielding gas	Helium, at 125 cfh
Power supply	600 amp, constant current, controlled to 1% variation; 100% duty cycle	Electrode stickout	⅜ in.
Mechanization	Welding head mounted on progressive welding boom, with vertical up-and-down travel	Current	225 amp, dcsp
Fixtures	Twelve leveling fixtures; eight chucks; clamping straps; welding fixture	Voltage	11 to 13 v
		Filler-metal feed	22 ipm
		Welding speed	6 ipm
		Setup time	8 hr
		Weld time	30 to 40 min
Torch	Water cooled	Number of passes	One

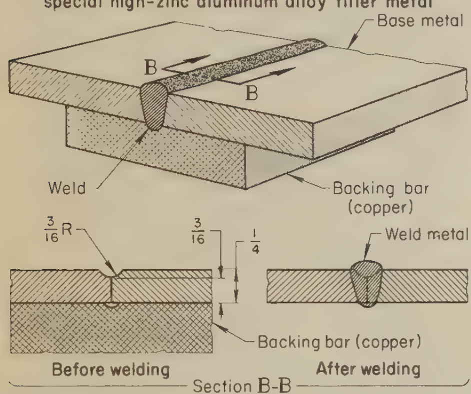
Fig. 48. Welded aluminum cylindrical shell, showing fixtures, and joint before and after welding (Example 319)

Table 34. Aging Treatments, Properties Obtained in Transverse-Weld Specimens, and Welding Conditions for Alloy 7075 and 7079 Plate (Example 321)

Alloy 7075-T6; aluminum alloy filler metal (ER5183)



Alloy 7079-T6; special high-zinc aluminum alloy filler metal



Time at aging temperature	Tensile strength, psi	Yield strength, psi	Elongation in 2 in., %
Alloy 7075 Plate, 5/8 In. Thick(a)			
4 hr	63,300	53,600	6.0(b)
Alloy 7079 Plate, 1/4 In. Thick			
Aged at room temperature			
8 hr	42,400	28,900	4.0
1 wk	50,200	35,800	3.0
2 wk	51,400	35,900	3.0
3 wk	52,800	37,300	3.0
4 wk	52,900	37,400	4.5
6 wk	52,300	36,600	4.0
12 wk	53,600	38,100	3.5
Aged at 200 F			
4 hr	50,600	36,700	3.0
8 hr	51,400	37,500	3.5
12 hr	51,100	37,800	3.0
24 hr	52,400	38,900	3.0
48 hr	54,500	43,600	2.0
Aged at 225 F			
4 hr	49,500	36,000	2.5
8 hr	51,300	38,400	3.0
12 hr	51,200	38,100	3.5
24 hr	54,400	42,400	2.5
48 hr	54,900	42,600	2.5

Item	Alloy 7075	Alloy 7079
Semiautomatic Gas Tungsten-Arc Welding		
Joint type	Butt	Butt
Weld type	Double-V	Single-U
Welding position .	Flat	Flat
Weld backing	None	Copper bar
Filler metal	ER5183	(c)
Filler-metal diam .	1/16 in.	1/16 in.
Shielding gas	Helium	Helium
Gas-flow rate	75 cfh	100 cfh
Current (dcsp) ...	270 amp	205 amp
Filler-metal feed .	30-40 ipm	30-33 ipm
Welding speed	10-12 ipm	6 ipm
Number of passes .	Two	One

(a) Average of values after aging for 4 hr at 200, 250 and 315 F. (b) Elongation in 1.4 in. (c) 4.4% Zn, 2.8% Mg, 1.0% Cu, remainder Al.

Table 35. Common Problems With Gas Tungsten-Arc Welding and Their Usual Causes

Arc-Starting Difficulty

1 Incorrect adjustment of high-frequency spark gap
2 Incomplete welding circuit

Inadequate Cleaning Action by the Arc

1 Incorrect adjustment of high-frequency unit or battery bias
2 Open-circuit voltage too low
3 Inadequate gas shielding, caused by:
  Insufficient gas flow
  Spatter on inside of gas nozzle
  Contact tube off-center in relation to gas nozzle
  Wrong nozzle-to-work distance
  Incorrect position of welding torch
  Drafty environment

Dirty Weld Bead

1 Insufficient shielding-gas coverage, caused by:
  Insufficient gas flow
  Damaged or dirty gas nozzle
  Wrong nozzle-to-work distance
  Incorrect position of welding torch
  Contact tube off-center in relation to gas nozzle
  Wrong nozzle size (use smallest possible)
  Drafty environment
  Impurities in shielding gas, due to air or water leakage
2 Poor cleaning action by the arc (see causes listed under the heading "Inadequate Cleaning Action by the Arc", above)
3 Unstable arc (use battery bias)
4 Electrode contamination
5 Dirty workpieces or filler metal

Electrode Contamination by Aluminum

1 Improper manipulation of torch
2 Excessive electrode extension
3 Wrong electrode material (use zirconiated electrode with alternating current)

Incorrect Electrode Contour

1 Incorrect electrode size for current
2 Incorrect contouring of electrode end before welding
3 Wrong electrode material (use zirconiated electrode with alternating current)

Weld-Bead Contamination by Electrode

1 Electrode size too small for current
2 Improper manipulation of torch
3 Wrong electrode material (use zirconiated electrode with alternating current)

Rough Weld Bead

1 Unstable arc
2 Improper manipulation of torch
3 Incorrect current

Weld Bead Too Wide

1 Excessive current
2 Welding speed too low
3 Arc too long
4 Electrode stickout too short
5 Incorrect position of welding torch

Inadequate Penetration

1 Wrong edge preparation for the arc characteristics (groove too narrow)
2 Excessive filler metal in weld puddle
3 Insufficient current
4 Arc too long
5 Welding speed too high

Difficulty in Adding Filler Metal

1 Improper manipulation of welding torch or filler metal, or both
2 Incorrect current, welding speed or filler-metal size
3 Incorrect adjustment of high-frequency unit
4 Poor insulation on high-frequency unit or leads
5 Incorrect operation of battery bias (connections may be reversed)

Poor Visibility of Arc and Weld Puddle

1 Wrong position of work
2 Incorrect position of welding torch
3 Small or dirty lens helmet
4 Wrong size of gas nozzle (use smallest possible)

Overheating of Power Supply

1 Excessive power demand (two similar welding machines can be operated in parallel if the capacity of one is insufficient)
2 Poor functioning of cooling fan
3 Poor grounding of high-frequency unit
4 Poor functioning of bypass capacitor
5 Poor functioning of battery bias
6 Dirty rectifier stacks (regular maintenance required)

Overheating of Welding Torch, Leads and Cables

1 Loose or faulty connections
2 Welding torch, leads or cables too small
3 Inadequate cooling-water flow

Welder Fatigue

1 Wrong position of work (weld in flat position whenever possible)
2 Inadequate seating arrangement for welder
3 Lack of ventilation
4 Disregard of safety rules regarding head shield, lens, gloves
5 Weight of cables (reduce by suspending cables overhead)
6 Too many auxiliary operations, such as cleaning and chipping (provide additional help)

sen for this application because of its combination of good base-metal strength at elevated temperature, good weld strength, and good weldability compared to other high-strength, heat treatable aluminum alloys. High-quality welds were required.

The four segments were produced from plates 120 in. wide by 311 in. long and 2 in. thick by curving them in the long direction to a 16½-ft radius and mechanically milling the concave side to various final thicknesses. Vertical stiffening ribs 2 in. thick, top and bottom rims, and 2-in.-wide lands 0.406 in. thick (and thus with root faces 0.406 in. wide) were left on the plates. Other areas of the plates were machined to various thicknesses up to 0.25 in., which was the thickness that adjoined the weld lands. The extra thickness of the weld lands was designed to compensate for the lower unit strength of the weld area compared with that of the base metal.

The procedure for making the welds was as follows:

1 Clean the areas to be welded, both chemically and mechanically.
2 Place shell segments on leveling fixtures and against chucks to form the cylinder. Position clamping straps inside the top rim and clamp in place. Clamp welding fixture in place with two vacuum chucks, one on either side of the joint.
3 Check joint alignment and spacing.
4 Manually weld aluminum runoff tabs, 6 in. square, top and bottom of each joint.
5 Make 1-in. tack welds manually on 6-in. centers.
6 Check equipment.
7 Automatically weld four 10-ft-long joints in one pass each, on inside of cylinder.
8 Inspect visually and radiographically.
9 Remove runoff tabs.

With the machine settings used, it was not necessary to use a backing bar, but the back of the weld was cooled with excess helium gas from the welding operation. The weld was made in one pass, with only minor distortion. If the weld lands had been thicker, thus providing wider root faces, or if less distortion than the minor amount obtained had been required, a double-welded joint with one pass from each side would have been used, as discussed in the following example. Welding conditions are shown in the table that accompanies Fig. 48.

Example 320. Automatic Straight-Polarity Direct-Current Gas Tungsten-Arc Welding of 1-In.-Thick Alloy 2219 (Fig. 49)

A Y-shape ring machined from a rectangular forging was used as a transition fitting between the large-diameter cylindrical

shell and the bulkhead of a rocket-propellant tank, as shown in Fig. 49. Welding of the alloy 2219-T87 cylinder is described in Example 319. In welding the Y-ring to the cylinder, the 1.000-in. wall thickness required two weld passes, one from each side.

The workpieces were alkaline cleaned and deoxidized, and the joint edges were mechanically scraped to bare metal before welding. They were then mounted on a rotating table powered by a 3-hp-drive motor with proportional and integral servo-amplifier speed control. Two welding units were used: one outside and one inside the cylinder. The unit inside the cylinder was placed so that its weld puddle lagged approximately 4 ft behind the weld puddle of the outside unit. Both welding units were equipped with sequence control for programing starts and stops and were also equipped with a cold filler-wire feed driven by a closed-loop velocity servo system.

Tack welds 2 in. long were made on 6-in. centers around the full circumference of the cylinder. Penetration was established before rotation of the workpiece started. Welding was done simultaneously from both sides using the "buried-arc" technique in which fairly low arc voltage and a high current were used, the electrode following the concave molten weld puddle below the original workpiece surface. With this technique, deep penetration and narrow welds were obtained at fairly high welding speed. Weld-quality requirements were severe; virtually no porosity or defect was allowed.

Setup time was about 8 hr, and welding time was 5 hr per joint.

Although the welding of some of the high-strength heat treatable alloys, such as 7075 and 7079, is not recommended, they can be gas tungsten-arc welded with straight-polarity direct current by skilled welders using special techniques. A welding technique that will ensure retention of the high strength of the base metal, and that will prevent cracking of the weld metal and allow development of maximum weld-metal strength is imperative. Full postweld heat treatment (solution heat treatment, quenching, and aging) results in the highest strength, but solution heat treatment and quenching often causes excessive warping of the part, and thick sections are difficult to quench effectively. A combination of welding conditions and postweld aging that produced good results in one application is noted in the next example:

Example 321. Welding Plate of High-Strength Alloys 7075 and 7079 (Table 34)

Butt welds between two plates of alloy 7075-T6, ⅝ in. thick, and two plates of alloy 7079-T6, ¼ in. thick, were made by the gas tungsten-arc process. The joint design for the 7075 plates was a double-V groove with a 5⁄16-in. root face, and for the thinner 7079 plates, a single-U groove with a 3⁄16-in. root face. The large root faces and small grooves for both welds favored substantial alloying of the base metal in the weld metal, as shown in the table below:

Element	Base metal	Filler metal(a)	Weld metal
Welding Alloy 7075 Plate			
Zinc, %	5.1-6.1	0.25 max	4.10
Magnesium, %	2.1-2.9	4.3-5.2	2.50
Copper, %	1.2-2.0	0.10 max	1.20
Welding Alloy 7079 Plate			
Zinc, %	3.8-4.8	4.4	4.75
Magnesium, %	2.9-3.7	2.8	2.50
Copper, %	0.4-0.8	1.0	1.10

(a) Filler metal ER5183 was used in welding the alloy 7075 plate, and a special high-zinc alloy of the composition shown was used in welding the alloy 7079 plate.

The weld metal in both joints had about the same zinc and magnesium contents as alloy 7039 (3.5 to 4.5% Zn, 2.3 to 3.3% Mg), which is readily arc weldable and is strengthened by natural aging.

The postweld aging treatments and the properties obtained in the weld metal for both alloys are shown in Table 34, along with the welding conditions.

Problems in Gas Tungsten-Arc Welding of Aluminum Alloys

Many of the problems that are encountered in gas metal-arc welding of aluminum alloys are also present in gas tungsten-arc welding. Common problems and their causes are summarized in Table 35.

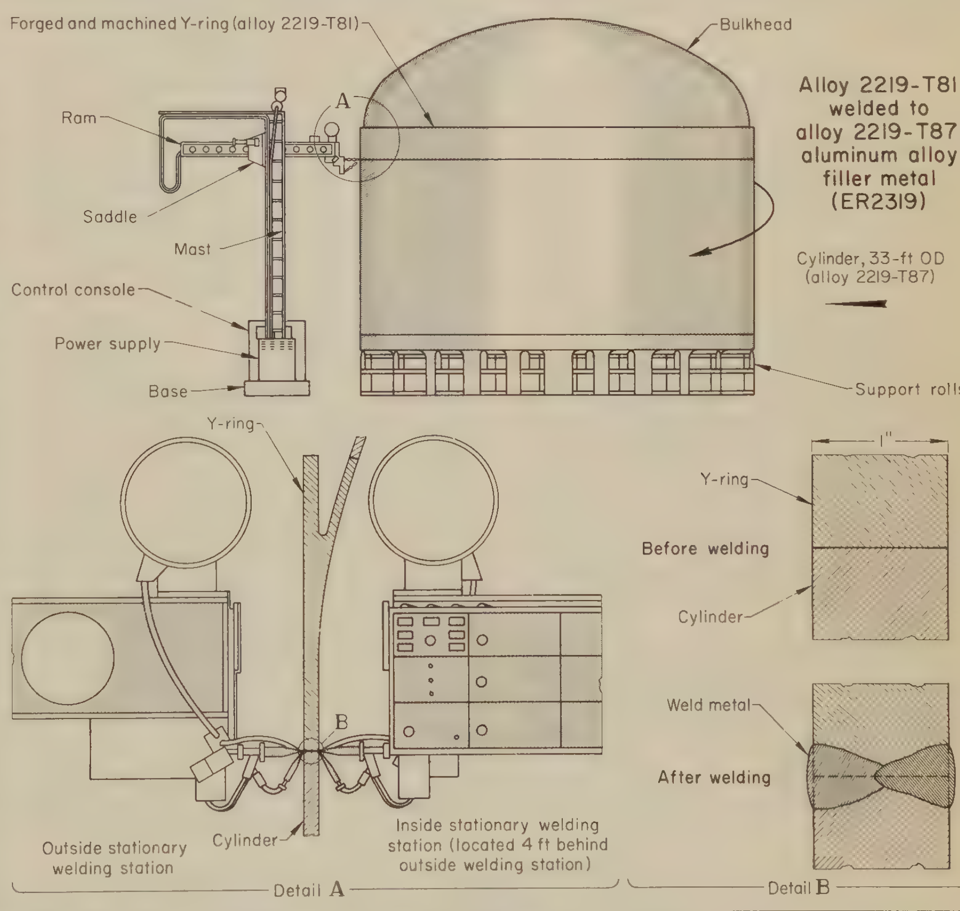
Dirty workpieces and filler metal can result in a dirty weld bead and an unsound weld. Preweld cleaning of workpieces is described in the section on page 297 of this article. An effective test for cleanness of filler metal is described in Example 311 on page 326.

Improper fixturing can also result in weld defects. For instance, when a rough and uneven weld bead with excessive porosity and areas of incomplete fusion was encountered on a corner weld in alloy 6061, investigation showed that the magnetic field surrounding the arc had been deflected by the nearby carbon steel fixturing, which had caused arc instability. Changing to a nonmagnetic fixturing material ended the trouble. Aluminum fixturing was tried, but it became loose on heating. Austenitic stainless steel proved satisfactory.

In other applications, excessive spatter of tungsten was ended by changing from an unalloyed tungsten electrode to a thoriated tungsten electrode; complete penetration was obtained when the ⅛-in.-diam filler-metal wire was replaced with a 1⁄16-in.-diam wire.

Gas Metal-Arc Welding vs Gas Tungsten-Arc Welding

The uses of gas metal-arc and gas tungsten-arc welding overlap to some extent. The general merits of the two



Conditions for Automatic Gas Tungsten-Arc Welding (dcsp)

Joint type	Butt	Torch	Water cooled
Weld type	Square groove	Gas nozzle	⅝-in. diam
Welding position	Horizontal	Electrode	5⁄32-in.-diam EWTh-2
Power supply	600 amp, constant current, controlled to 1% variation; 100% duty cycle	Filler metal	1⁄16-in.-diam ER2319(a)
Mechanization	Automatic arc-voltage control to 0.1% variation; wire-feed system; 360° rotation of work on motor-drive table	Shielding gas	Helium, at 120 cfh
Wire-feed system	1 to 100 ipm, controlled to 1% variation	Voltage	11.5 to 12.5 v
		Filler-metal feed	1 in. of wire per inch of travel
		Welding speed	2 to 5 ipm
		Number of passes	Two

(a) Wire was stored in a hermetically sealed container before use, and was fed from dustproof containers during welding.

Fig. 49. Automatic gas tungsten-arc welding of a forged and machined Y-ring to a 33-ft-diam cylinder, showing placement of welding heads for making welds on the inside and outside of the cylinder and ring (Example 320)

Table 36. Comparison of the Gas Metal-Arc and the Gas Tungsten-Arc Processes for Welding Aluminum Alloys

Application considerations	Relative rating(a) Gas metal-arc	Gas tungsten-arc
Cost Factors		
Cost of equipment	B	A
Maintenance of equipment	B	A
Operating factor (output)	A	B
Volume of metal deposited	A	B
Welding rate	A	B
Versatility		
Welding with filler metal	A	B
Welding without filler metal	NA	A
Welding metal thinner than ⅛ in.	A	A
Welding metal thicker than ⅛ in.	A	B
Out-of-position welding	A	B
Making short welds	B	A
Making welds having abrupt changes in contour	B	A
Low welding speed possible	B	A
Weld Quality		
Strength	A	A
Ductility	A	A
Corrosion resistance	A	A
Absence of defects	A	A
Penetration	A	A
Distortion	A	A
Welding of Castings		
General reclamation	B	A
Reclamation to specification	B	A
Repair welding	B	A
Fabrication with castings	A	B

(a) An A rating is better than a B rating. NA indicates process is not applicable.

processes are compared in Table 36. Individual applications should be considered in detail, with reference to Table 36 and the following factors.

Advantages of Gas Metal-Arc Welding. Most of the advantages of gas metal-arc welding over gas tungsten-arc welding stem from the fact that in gas metal-arc welding reverse-polarity direct current is used at a high current density. This is possible because the electrode is consumable and is melted during the welding, whereas in gas tungsten-arc welding the current is limited by the melting temperature of the electrode. Heat transfer by the arc is very efficient.

High Welding Rate. Welding speeds two to three times those obtainable by manual gas tungsten-arc welding are possible, particularly when welding metal more than ⅜ in. thick. When machine welding thinner metal, the welding speed is about the same for the two processes.

In manual gas tungsten-arc welding, the length of welding is somewhat limited by the length of filler-metal rod that the welder can conveniently handle; he usually cannot make a weld longer than 12 in. without breaking the arc.

The gas metal-arc process and the automatic gas tungsten-arc process share the feature that the filler metal is added mechanically, and the operator is usually able to weld at least 24 in. without having to break the arc and change position. Therefore, with these latter processes less time is lost in starting and stopping, which results in fewer weld craters and more feet of weld per hour. They are also less fatiguing than the manual gas tungsten-arc process because the operator does not have to coordinate the movement of both hands, and he can continue welding for a greater length of time, a factor that contributes to higher welding rates.

Lower Welding Cost on Metal More Than ¼ In. Thick. The equipment used for gas metal-arc welding is more expensive than that used for gas tungsten-arc welding, but on thick sections requiring multiple-pass welding (generally more than ¼ in. thick), the higher welding rates of the gas metal-arc process generally result in lower welding cost.

Low Distortion. Because of the high welding speed, which results in rapid chilling of the weld area, distortion is generally low. The distortion produced on aluminum with the gas metal-arc process is no more, and is usually less, than that produced on steel of the same thickness when it is welded with flux-cored electrodes. As soon as the arc is established, filler metal is added to the joint, which aids in preventing distortion when sheet is being welded to thicker framing members.

Good Weld Quality. The quality of welds produced by the gas metal-arc process using spray transfer is of a very high order.

Good Out-of-Position Welding. Because the appreciable arc force projects the weld metal across the arc at a high velocity, not affected by gravity, welding can be done in any position.

High Deposition Rate. Where a high rate of filler-metal deposition is required, as in welding heavy sections or in building up a surface, the gas metal-arc process has a considerable advantage. High rates of metal deposition are easy to obtain with the large-diameter filler wires (up to ⅜2 in. in diameter) when they are used with high welding currents.

Readily Adapted to Machine Welding. Because of its semiautomatic nature, the gas metal-arc process can be readily adapted to automatic welding for metal from 0.030 in. thick to the thickest commercially available. Automatic gas tungsten-arc welding requires good control of joint fit-up, usually within 0.003 to 0.010 in., depending on material thickness, but gas metal-arc welding is less sensitive to variations in fit-up.

Freedom From Radio Interference. Gas metal-arc welding employs direct current, and so it is not necessary to use high-frequency current for arc stabilization, which means that there is no radio interference as there may be when using high-frequency current with gas tungsten-arc welding.

Table 37. Approximate Costs of Gas Metal-Arc and Gas Tungsten-Arc Welding Equipment

Electrode-wire diameter, in.	Cost: Welding unit(a)	Cost: Power supply	Cost: Total	Thicknesses to be welded, in.
Gas Metal-Arc Welding Equipment				
0.030 to ³⁄₃₂	$2200	$900 to $1350	$3100 to $3550	0.040 to over 3

Machine capacity, amp	Cost: Alternating-current unit(b)	Cost: Welding torch	Cost: Total	Thicknesses to be welded, in.
Gas Tungsten-Arc Welding Equipment				
200	$ 800 to $ 900	$200	$1000 to $1100	0.020 to ³⁄₁₆
300	950 to 1050	200	1150 to 1250	0.020 to ⁵⁄₁₆(c)
400	1000 to 1100	200	1200 to 1300	0.020 to ⅜(c)
500	1100 to 1200	200	1300 to 1400	0.020 to ½(c)

(a) Including wire feeder, control panel, welding torch, and secondary contactor. (b) Including high-frequency unit and water and gas controls. (c) Being able to weld 0.020-in.-thick metal depends on ability to reduce current output of machine below normal rated output.

Table 38. Pounds per Foot, and Feet per Pound, of Various Diameters of Aluminum Alloy Filler-Metal Wire (a)

Wire diam, in.	Pounds per foot	Feet per pound
0.030	0.000848	1180
0.035	0.001153	867
0.040	0.001508	664
³⁄₆₄	0.00207	484
¹⁄₁₆	0.00368	272
³⁄₃₂	0.00828	121
⅛	0.01473	68
⁵⁄₃₂	0.0230	44
³⁄₁₆	0.0332	30
⁷⁄₃₂	0.0451	22
¼	0.0589	17

(a) Based on a density of 0.100 lb per cubic inch. For correction factors for alloys of other densities, see Table 39.

Advantages of Gas Tungsten-Arc Welding. Most of the advantages of gas tungsten-arc welding stem from the fact that the filler metal is introduced separately into the arc, which allows the welding current and wire speed to be independently adjusted.

Lower Welding Costs on Metal Less Than ⅛ In. Thick. In automatic welding, where attainable welding speed is nearly equal to that used in gas metal-arc welding, greater economy is usually realized with the gas tungsten-arc process, because welding current and wire speed can be independently adjusted to reduce the consumption of filler metal to the minimum. However, in semiautomatic welding, greater economy is generally realized with the gas metal-arc process because welding speed is two to three times faster than that obtainable with the gas tungsten-arc process.

The equipment used for gas tungsten-arc welding is less expensive than that used for gas metal-arc welding, and needs less maintenance.

Very Thin Material Can Be Welded. Using a pulsed arc, the gas metal-arc process can be used to weld metal as thin as 0.040 in., but metal as thin as 0.010 in. can be welded by the gas tungsten-arc process, provided the workpieces are correctly aligned and held.

Butt Welds Can Be Made in Small Shapes. Because filler metal is added manually to the weld in manual gas tungsten-arc welding, the welder has complete control of the weld puddle at all times. This is a definite advantage in butt welding small and medium angles and other shapes in which heat requirement at the toe of the angle is less than at the heel.

Welds Can Be Made Without Filler Metal. This is important in fusing together the edges of a butt joint or the edge of a lap joint, to make smooth welds that require little grinding or cleaning.

Excellent Weld Quality. The quality of welds made by the gas tungsten-arc process is of a very high order, and the process offers excellent reliability. When welding thick material by the gas tungsten-arc process, the filler metal need not be added to the weld until the base metal has been well penetrated; with the gas metal-arc process, filler metal is added as soon as the arc is struck, which sometimes prevents penetration and causes cold starts. Preheating thick material to 200 to 250 F ensures satisfactory starts when gas metal-arc welding; otherwise, cold starts must be chipped out and rewelded.

Cost of Welding. The over-all cost of welding comprises capital expenditure for equipment, the actual welding expenses, and the cost of material preparation and finishing (edge preparation, cleaning, fitting, assembling, handling, and surface finishing). The actual welding expenses are the cost of filler-metal wire, gas, overhead, labor, and maintenance of welding equipment. Ordinarily, the process that enables a

Table 39. Correction Factors for Density of Aluminum Filler-Metal Alloys

Filler alloy	Density, lb/cu in.	Factor(a) Lb/ft	Ft/lb
ER1100	0.098	0.98	1.02
ER1260	0.098	0.98	1.02
ER2319	0.103	1.03	0.97
ER4043	0.097	0.97	1.03
ER4047	0.097	0.97	1.03
ER4145	0.101	1.01	0.99
ER5039	0.097	0.97	1.03
ER5183	0.096	0.96	1.04
ER5356	0.095	0.95	1.05
ER5554	0.097	0.97	1.03
ER5556	0.095	0.95	1.05
ER5654	0.096	0.96	1.04
R-C4A	0.101	1.01	0.99
R-CN42A	0.102	1.02	0.98
R-SC51A	0.098	0.98	1.02
R-SG70A	0.097	0.97	1.03

(a) Multiply value in Table 38 by this factor.

weldment to be made in the minimum time is the most economical.

The amount of welding, and whether or not it is repetitive, influence the selection of a welding process and auxiliary equipment. Large amounts of welding will usually justify a considerable investment in welding equipment, jigs and fixtures.

In computing welding costs, it is usually assumed that the arc is maintained for only 33% of the time — that is, the operator welds for only 20 min of each hour. On certain production jobs where fast-operating jigs are employed, the operating factor may exceed 33%, and on those where a large amount of time for fit-up is required, or where only one assembly is being made, the operating factor may be much less than 33%.

In selecting a welding process, cost of equipment should be weighed against its advantages, because often the cost of an expensive piece of equipment can be offset by increased production and a higher-quality product. For a small production lot, high equipment cost can be justified only if the equipment is required for special reasons of quality or accessibility, or if future high-production use is anticipated. Table 37 gives the approximate costs of equipment for gas tungsten-arc welding and gas metal-arc welding. The gas tungsten-arc units described are standard alternating-current arc welding machines having a built-in high-frequency unit and gas and water controls. The machines can be converted for the welding of steel by operating a switch to bypass the high-frequency unit and gas and water controls.

Weights of aluminum welding wire of various diameters and correction factors for alloys are given in Tables 38 and 39, respectively.

Selection of Process. Availability of equipment may determine the process to be used for a given application, but generally selection is based on the capability of a process to meet joint requirements, and on cost. When the thickness of aluminum sheet reaches about 3⁄16 in., the use of the automatic gas tungsten-arc process with alternating current for single-pass butt welding becomes prohibitively slow, although joint quality is excellent. The same joints in this thickness and above can be single-pass welded at a much higher speed using gas tungsten-arc welding with straight-polarity direct current, because of the narrower and deeper penetration obtained, but more careful edge cleaning is needed to ensure high joint quality. Both processes are capable of producing welds to high quality standards, and joint thickness becomes a consideration when deciding which to use.

Aluminum sheet 3⁄16 in. or more in thickness can also be welded by the gas metal-arc process using spray transfer and at much higher speeds. Because reverse-polarity direct current is used, edge cleaning is less critical than for gas tungsten-arc welding with straight-polarity direct current. Joint quality is good and easily meets commercial requirements.

In Table 40, these three processes are roughly compared for mechanized welding of butt joints in ¼-in.-thick aluminum alloy plate, using hold-down clamps and a grooved backing bar. The illustration in Table 40 shows the two most commonly used types of edge preparation for these joints — square grooves and single-V grooves.

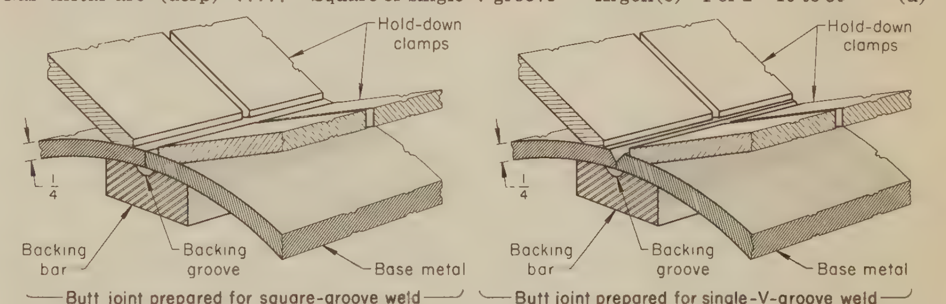
The use of gas tungsten-arc welding with alternating current, as indicated in Table 40, would necessitate edge preparation in the form of a single-V groove to obtain complete penetration. The welding speed of this process is relatively low, and the effective welding speed for the joint is only half the actual welding speed, because two passes are needed to fill the joint. Sound weld metal is produced.

Gas tungsten-arc welding with straight-polarity direct current can be done at a relatively high welding speed, and deep penetration is obtained. Although the square-groove edge preparation shown in Table 40 to be applicable for this process does not entail beveling, to obtain optimum weld-metal soundness joint edges must be cleaned chemically and mechanically (by filing or scraping) before welding. Starts and stops must be regulated by current-control devices, or must be eliminated completely by means of starting and runoff tabs.

Gas metal-arc welding of the joints shown in Table 40 can be accomplished at high welding speed, depending on the quality and reliability demanded of the weld, but it is more difficult to establish and maintain precise control

Table 40. Comparison of Three Arc Welding Processes for Welding Butt Joints in ¼-In.-Thick Aluminum Alloy Plate

Welding process	Edge preparation (weld type)	Shielding gas	No. of passes	Typical welding speed, ipm	Suitability of process
Gas tungsten-arc (ac)	Single-V groove	Argon	2	4 to 8	(a)
Gas tungsten-arc (dcsp)	Square groove	Helium	1	12 to 20	(b)
Gas metal-arc (dcrp)	Square or single-V groove	Argon(c)	1 or 2	10 to 50	(d)



(a) Suitable for nuclear and aerospace applications, but too slow. (b) Suitable for nuclear and aerospace applications. (c) Helium additions up to 80% improve radiographic quality. (d) Suitable for commercial applications — both code (pressure vessel, piping) and noncode applications.

Table 41. Comparison of the Gas Tungsten-Arc and the Gas Metal-Arc Processes for Welding of Butt Joints in 0.160-In.-Thick Alloy 5456 Sheet(a)

Item	Automatic gas metal-arc welding	Automatic gas tungsten-arc welding
Welding Conditions		
Current, amp	160, dcrp	260, ac
Voltage, v	24	12
Shielding gas	Argon-helium, at 60 cfh(b)	Argon, at 25 cfh
Welding speed, ipm	22	15
Costs per Lineal Foot of Weld		
Labor and burden(c)	$0.237	$0.280
Gas	0.087	0.054
Cleaning(d)	0.022	...
Total	$0.346	$0.334
Weld Quality		
X-ray standard(e)	Class II	Class I
Appearance	Uniform bead width and contour, rough penetration, excessive spatter on weld-face side	Very uniform bead width, excellent surface appearance, smooth penetration, well-fused edges
Mechanical properties:		
Yield strength, psi	23,300	24,450
Tensile strength, psi	47,700	49,800
Elongation, %	6	9.5

(a) Single-pass welds in square-groove butt joints. (b) 30 cfh of argon and 30 cfh of helium. (c) Includes wages of operator, based on 50% welding time, and administrative, general overhead, and amortization costs. (d) Includes removal of spatter and discoloration, and dressing of rough starts. (e) Class standards as defined by MIL-R-45774.

over welding variables in gas metal-arc welding than in gas tungsten-arc welding. For example, arc length, burnoff rate, wire-feed speed, and current and voltage are directly related in gas metal-arc welding. The butt joints in Table 40 could be welded in a single pass with high reinforcement if square-groove edge preparation were used, or in two passes with limited reinforcement if single-V-groove edge preparation were used. Although argon is normally used in gas metal-arc welding of metal up to ¾ in. thick, radiographic quality of the weld metal can be improved by the addition of up to 80% helium.

For welding the joints shown in Table 40, the first process, gas tungsten-arc welding with alternating current, is too costly; it would be used only if no other process were available. As between gas tungsten-arc welding with straight-polarity direct current and gas metal-arc welding, weld-quality requirements would be the deciding factor. Gas tungsten-arc welding is capable of meeting the highest standards of nuclear and aerospace applications; gas metal-arc welding is capable of meeting the requirements of pressure-vessel and piping codes, as well as other commercial standards, where high deposition rates are more important than in nuclear and aerospace applications.

When the aluminum sheet thickness is less than 3/16 in., the gas tungsten-arc process becomes competitive with gas metal-arc welding. The costs for making a single-pass square-groove butt weld in 0.160-in.-thick alloy 5456 sheet by the gas tungsten-arc and gas metal-arc processes are compared in Table 41. Although the power supply and tooling costs are roughly the same for both processes, the other equipment costs for gas metal-arc welding can be $2000 more. This adds to the amortization costs and lessens the advantage of the lower labor and burden costs. In Table 41, the higher costs for shielding gas and postweld cleaning more than offset the lower labor and burden costs of making the weld by the gas metal-arc process, so that the over-all cost of producing the welded joint was less for the gas tungsten-arc process. In addition, gas tungsten-arc welding produced a weld that had better quality, needed less repair welding and developed higher mechanical properties.

In the following example, both the automatic gas tungsten-arc and the automatic gas metal-arc processes were found acceptable for making fillet welds between ¼ and ½-in. stock. The welding speeds were similar enough so that the welding cost differences became less important than the availability of equipment.

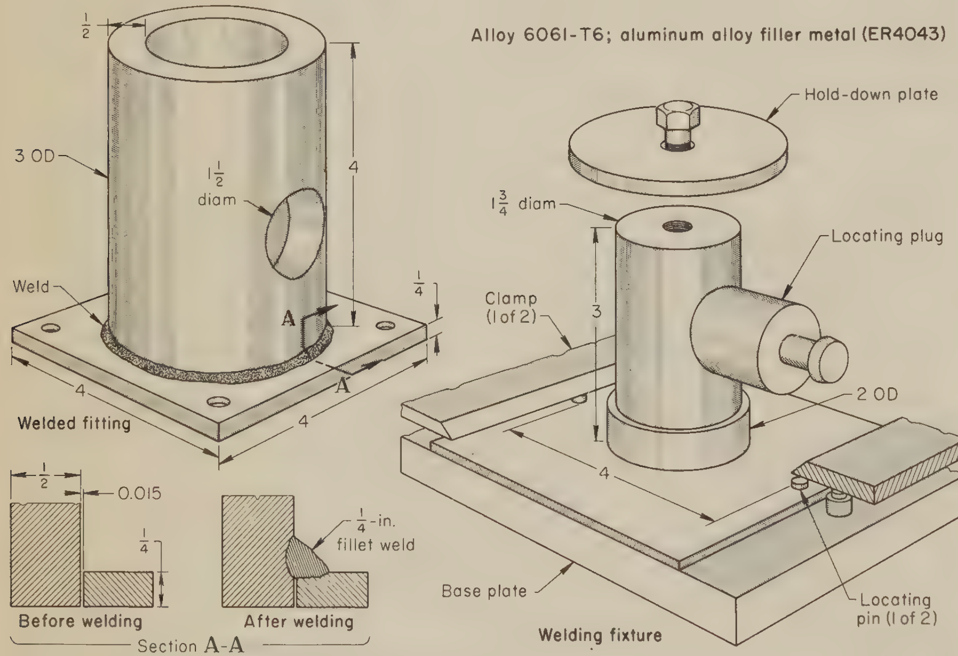
Example 322. Approval of Both Automatic Gas Tungsten-Arc and Automatic Gas Metal-Arc Processes for Welding Alloy 6061 (Fig. 50)

For joining the alloy 6061-T6 aircraft bypass fitting shown in Fig. 50, several processes were considered. Oxyacetylene welding was tried, but without success. The heat was dissipated too rapidly, and the resulting weld was not up to the standard required. The assembly could have been furnace brazed, but this method was unacceptable because: (*a*) in order to make the part to close tolerances to provide close fits, the tooling would have had to be changed; and (*b*) there was no brazing furnace available in the plant and so brazing would have had to be subcontracted, which would have added to the cost.

The part was successfully welded by the gas tungsten-arc process. Manual welding, using alternating current, was tried first. This met all aircraft standards and engineering requirements, but it was very slow, even though small turntables were used to rotate the part. Automatic gas tungsten-arc welding made fully satisfactory welds. A voltage-controlled contour welding machine with automatic wire feed was combined with an adjustable torch-holding carriage and a turntable that were already available. A welding fixture (see Fig. 50) was designed to fit on the turntable. The use of automatic welding resulted in the required increase in welding speed.

Although gas metal-arc welding was not extensively used in the plant, because most aluminum alloy parts welded were too thin for the process, it was tried for the bypass fitting, in which sections were fairly thick (¼ and ½ in.). The same fixture, turntable and carriage as those used for automatic gas tungsten-arc welding were used for automatic gas metal-arc welding. The results were good. Etching and face-bending tests met the requirements for the assembly.

Welding time was slightly less for gas metal-arc welding than for gas tungsten-arc welding, but both automatic processes were approved and used. This was one of the few assemblies for which both processes were permitted.



Item	Automatic gas tungsten-arc welding	Automatic gas metal-arc welding
Joint type	Corner	Corner
Weld type	Fillet	Fillet
Root opening, in.	0.015	0.015
Welding position	Flat	Flat
Power supply	300-amp transformer-rectifier	300-amp transformer-rectifier
Mechanization	Turntable	Turntable
Filler-wire feed system	Automatic, push	Automatic, push
Fixtures	Assembly, clamping	Assembly, clamping
Edge preparation	Deburring	Deburring
Torch or electrode holder	Water cooled, held at 40° angle	Air and gas cooled
Filler metal	3/64-in.-diam ER4043-H18	3/64-in.-diam ER4043-H18
Shielding gas	Helium, at 20 cfh	Argon, at 20 cfh
Electrode stickout, in.	½	⅜
Current, amp	200, dcsp	Dcrp; amperage not recorded
Voltage, v	15	40
Filler-metal feed, ipm	230	240
Welding speed, ipm	14	15
Number of passes	One	One

Fig. 50. An aircraft bypass-fitting assembly that could be welded by either the automatic gas tungsten-arc or the automatic gas metal-arc process in approximately the same welding time, both producing welds that met quality standards, and the fixture used for welding by both processes (Example 322)

Other Arc Welding Processes

In addition to being welded by the gas metal-arc and gas tungsten-arc processes, aluminum alloys are sometimes joined by shielded metal-arc, stud, and percussion welding.

Shielded metal-arc welding is used primarily in small shops for miscellaneous repair work in noncritical applications. A flux-covered aluminum alloy electrode is used. The flux combines with aluminum oxide to form a slag. The slag must be removed after each weld pass. Weld soundness and surface smoothness are poor. The process is limited to butt welds in ⅛-in. and thicker aluminum. AWS A5.3-69 includes two covered electrodes: one with core wire corresponding to ER1100 and one to ER4043.

Stud welding of aluminum alloys is generally accomplished by the capacitor-discharge method, rather than the arc method. Examples 169, 172 and 174 in the article on Stud Welding (page 167) are illustrations of the stud welding of aluminum alloys.

Percussion welding of aluminum alloys is used principally for joining wire to wire. Numerous dissimilar metal joints, including aluminum to copper and to steel are made.

Arc Welding of Copper and Copper Alloys

*By the ASM Committee on Welding and Brazing of Copper and Copper Alloys**

COPPERS AND COPPER ALLOYS that are most frequently arc welded are listed in Table 1, which gives nominal compositions, melting points (liquidus temperatures) and relative thermal conductivities, and rates the materials as to weldability by the gas tungsten-arc, gas metal-arc, and shielded metal-arc welding processes. Leaded and other free-machining copper alloys are not ordinarily arc welded.

Gas tungsten-arc welding is the arc welding process most widely used for joining coppers and copper alloys. Desirable features of the process — particularly on the more heat-conductive copper alloys — are its intense localized heat input, good control, and suitability for use with or without filler metal. Gas tungsten-arc welding is used mainly for sections up to ⅛ in. thick, but good results can be obtained on sections up to ½ in. thick.

For sections more than ½ in. thick, gas metal-arc welding is preferred (when applicable), because of its high deposition rate and high heat input.

Shielded metal-arc welding is used in low-volume production to join copper and copper alloys because of its simplicity, low cost, versatility and the mobility of the equipment. Sometimes this process is used because of its suitability for welding odd-shape parts and where access to the work is difficult. Uniformity and quality of welds are generally lower than for the gas-shielded processes, especially for the more conductive copper alloys, and labor and material costs are higher.

Because of the reduction in strength, formation of oxides, or volatilization of elements that often accompany arc welding, brazing is frequently selected for joining copper alloys (see the article that begins on page 685).

Effects of Alloying Elements on Welding

Several alloying elements have pronounced effects on the welding behavior of copper and copper alloys. At least small amounts of volatile, toxic alloying elements are present in copper and its alloys, and, as a result, the use of an effective ventilation system to protect the welder or welding-machine operator and to recover dusts, fumes and mists is more critical than for ferrous metals (see section on Safety at the end of this article).

Free-Machining Additives (Pb, Te, S). Low-melting elements such as lead, tellurium and sulfur, which are sometimes added to copper alloys to improve machinability, make them susceptible to hot cracking in welding. The adverse effect on weldability begins to be evident at about 0.05% of the additive and is more severe with larger additions. Free-machining copper alloys (which usually contain from 0.5 to 3 or 4% Pb) are not ordinarily welded, and are not listed in Table 1.

Zinc reduces the weldability of all the brasses and nickel silvers shown in Table 1, approximately in proportion to the amount present.

In addition to reducing weldability, zinc also gives off toxic vapors, so that when the copper-zinc alloys are welded, efficient forced ventilation is mandatory and a recovery system should be used to condense the fumes (see section on Safety in this article).

Tin, in amounts of about 1 to 10%, as in the phosphor bronzes and tin brasses, does not interfere with arc welding. Compared with zinc, tin is less volatile and much less toxic, and usually is present in lower amounts.

Beryllium, aluminum and nickel form tightly adherent oxides that must be removed by cleaning before welding. Formation of these oxides on the heated copper alloy must be prevented by gas shielding or by fluxes, in conjunction with selection of the appropriate type of current.

Nickel oxides interfere with arc welding less than oxides of beryllium or aluminum. Thus, the nickel silvers and copper nickels are less sensitive to type of current.

Oxygen as gas or in cuprous oxide causes porosity and reduces the strength of welds made in alloys that do not contain enough phosphorus or other deoxidizer. Most copper alloys that are welded contain deoxidizing elements (usually phosphorus, silicon, aluminum, iron or manganese) that combine with oxygen. The same deoxidizers are included also in filler metals.

The soundness and strength of arc welds made in commercial coppers depend on the cuprous oxide content. Soundness increases as oxide content decreases. Best results are obtained for deoxidized coppers, because they are free from cuprous oxide and contain residual phosphorus. (See "Effect of Cuprous Oxide", on page 340, in this article.)

Silicon has a beneficial effect on the weldability of copper-silicon alloys, because of its deoxidizing and fluxing action. This effect, combined with low thermal conductivity, makes the silicon bronzes the most weldable of the copper alloys by arc processes.

Iron and Manganese. Iron, which is present in some special brasses, aluminum bronzes and copper nickels, in amounts of 1.4 to 3.5%, does not significantly affect the weldability of these alloys. Manganese, which is present in some of these alloys in lower concentrations than iron, has no measurable effect on welding.

Factors That Affect Weldability

Other than the elements that comprise a specific alloy, the principal factors that influence weldability are: thermal conductivity of the alloy being welded, shielding gas, type of current, joint design, welding position, and surface condition (cleanness). Effect of type of current is discussed under the individual processes and alloys.

Effect of Thermal Conductivity. The welding behavior of copper and copper alloys is strongly influenced by thermal conductivity, which varies greatly among these alloys.

Table 1 shows relative thermal conductivities that are based on the conductivity of alloy 102 (oxygen-free copper), which is 226 Btu/sq ft/ft/hr/°F at 68 F, as 100. The range shown in Table 1 is from 100, for alloys 102 and 110, to lows of 8 to 12 for nickel silvers and copper nickels, and 9 for alloy 655 (high-silicon bronze A). For comparison, the thermal conductivity of carbon steel — 30 Btu/sq ft/ft/hr/°F at 68 F — is 13 on this scale.

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Several of the examples presented in this article were contributed by members of other Metals Handbook welding committees. Eight examples in other articles in this volume also deal with welding of copper and copper alloys; these examples are identified in Table 17 on page 357.

Table 1. Nominal Compositions, Melting Points, Relative Thermal Conductivities, and Weldabilities of Wrought Coppers and Copper Alloys That Are Commonly Arc Welded

Alloy No.	Alloy name	Nominal composition, %	Melting point (liquidus), F	Relative thermal conductivity(a)	Weldability(b) GTAW	GMAW	SMAW
		OF and ETP Coppers					
102	Oxygen-free copper (OF)	99.95 Cu	1981	100	G	G	NR
110	Electrolytic tough pitch copper (ETP)	99.90 Cu, 0.04 O_2	1981	100	F	F	NR
		Deoxidized Coppers					
120	Phosphorus-deoxidized copper, low-P (DLP)	99.9 Cu, 0.008 P	1981	99	E	E	NR
122	Phosphorus-deoxidized copper, high-P (DHP)	99.9 Cu, 0.02 P	1981	87	E	E	NR
		Beryllium Coppers					
175	High-conductivity beryllium copper, 0.6%	96.9 Cu, 0.6 Be, 2.5 Co	1955	53-66(c)	F	F	F
170	High-strength beryllium copper, 1.7%	98.3 Cu, 1.7 Be	1800	27-33(c)	G	G	G
172	High-strength beryllium copper, 1.9%	98.1 Cu, 1.9 Be	1800	27-33(c)	G	G	G
		Low-Zinc Brasses					
210	Gilding, 95%	95 Cu, 5 Zn	1950	60	G	G	NR
220	Commercial bronze, 90%	90 Cu, 10 Zn	1910	48	G	G	NR
230	Red brass, 85%	85 Cu, 15 Zn	1880	41	G	G	NR
240	Low brass, 80%	80 Cu, 20 Zn	1830	36	G	G	NR
		High-Zinc Brasses					
260	Cartridge brass, 70%	70 Cu, 30 Zn	1750	31	F	F	NR
268, 270	Yellow brass, 65%	65 Cu, 35 Zn	1710	30	F	F	NR
280	Muntz metal, 60%	60 Cu, 40 Zn	1660	31	F	F	NR
		Tin Brasses					
442-445	Admiralty	71 Cu, 28 Zn, 1 Sn(d)	1720	28	F	F	NR
464-467	Naval brass	60 Cu, 39.25 Zn, 0.75 Sn(d)	1650	30	F	F	NR
		Special Brasses					
675	Manganese bronze A	58.5 Cu, 39 Zn, 1.4 Fe, 1 Sn, 0.1 Mn	1630	27	F	F	NR
687	Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2 Al (0.06 As)	1780	26	F	F	NR
		Nickel Silvers					
745	Nickel silver, 65-10	65 Cu, 25 Zn, 10 Ni	1870	12	F	F	NR
752	Nickel silver, 65-18	65 Cu, 17 Zn, 18 Ni	2030	8	F	F	NR
754	Nickel silver, 65-15	65 Cu, 20 Zn, 15 Ni	1970	9	F	F	NR
757	Nickel silver, 65-12	65 Cu, 23 Zn, 12 Ni	1900	10	F	F	NR
770	Nickel silver, 55-18	55 Cu, 27 Zn, 18 Ni	1930	8	F	F	NR
		Phosphor Bronzes					
505	Phosphor bronze, 1.25% E	98.7 Cu, 1.3 Sn (0.2 P)	1970	53	G	G	F
510	Phosphor bronze, 5% A	95 Cu, 5 Sn (0.2 P)	1920	18	G	G	F
521	Phosphor bronze, 8% C	92 Cu, 8 Sn (0.2 P)	1880	16	G	G	F
524	Phosphor bronze, 10% D	90 Cu, 10 Sn (0.2 P)	1830	13	G	G	F
		Aluminum Bronzes					
613	Aluminum bronze D, Sn-stabilized	89 Cu, 7 Al, 3.5 Fe (0.35 Sn)	1950	14	G	E	G
614	Aluminum bronze D	91 Cu, 6-8 Al, 1.5-3.5 Fe, 1 max Mn	1915	17	G	E	G
		Silicon Bronzes					
651	Low-silicon bronze B	98.5 Cu, 1.5 Si	1940	15	E	E	F
655	High-silicon bronze A	97 Cu, 3 Si	1880	9	E	E	F
		Copper Nickels					
706	Copper nickel, 10%	88.6 Cu, 9-11 Ni, 1.4 Fe, 1.0 Mn	2100	12	E	E	G
715	Copper nickel, 30%	70 Cu, 30 Ni	2260	8	E	E	E

(a) Based on the thermal conductivity of alloy 102 (226 Btu/sq ft/ft/hr/°F at 68 F) as 100. For comparison, carbon steel has a thermal conductivity of 30 Btu/sq ft/ft/hr/°F, which is 13 on this scale. (b) E = excellent, G = good, F = fair, NR = not recommended; for gas tungsten-arc welding (GTAW), gas metal-arc welding (GMAW), or shielded metal-arc welding (SMAW). (c) In the precipitation-hardened condition. (d) Alloys 443 and 465 contain a nominal 0.06% As; alloys 444 and 466, a nominal 0.06% Sb; alloys 445 and 467, a nominal 0.06% P.

In the welding of commercial coppers and lightly alloyed copper materials having high thermal conductivity, the type of current and shielding gas must be selected for maximum heat input, because heat is rapidly dissipated from the weld region.

Even the less-conductive copper alloys may require preheating (depending on section thickness), in spite of the concentrated heat input of arc welding processes. The interpass temperature should be the same as that for preheating. Copper alloys are not postweld heat treated as frequently as alloy steels are, but they may require controlled cooling, to minimize residual stress and hot shortness.

Shielding gas for the gas-shielded arc welding processes is usually argon, or argon plus 25 to 75% helium. Because helium costs from two to ten times as much per cubic foot as argon, it is advantageous to develop welding procedures compatible with the use of argon or high-argon mixtures whenever possible.

Argon or argon-helium mixtures produce more uniform welds than helium on copper alloys, give a more stable arc, and cause less weld spatter.

Helium alone or in mixtures with argon is preferred where high heat input is needed, as in welding of the highly conductive coppers or copper alloys. Helium gives about one-third greater heat input than does argon at equal welding current.

Joint design for arc welding of copper and copper alloys does not differ greatly from that used in the arc welding of steel. Sections up to ⅛ in. thick can be joined by use of square-groove welds without root openings. Thicker sections ordinarily are joined using either single-V-groove or double-V-groove welds with root faces not more than ⅛ in. wide.

Joint design and fixturing should be such as to minimize constraint and contraction stresses, and to make allowance for the high coefficient of expansion of copper and copper alloys, in order to prevent cracking, which may result from hot shortness of the base metal at temperatures close to and above the solidus.

Backing strips or rings are used more extensively than on steel, to avoid loss of molten metal, particularly on the highly fluid coppers and high-copper alloys. Backing strips and rings are usually made either of the alloy that is being welded, or of copper, carbon or graphite.

Joint and weld types used for arc welding of copper and copper alloys are illustrated in Table 5. Typical dimensions, root openings and groove angles for welding the various types of alloys are given in the tables of nominal welding conditions in this article.

Welding Position. The flat position is used whenever possible, because of the high fluidity of copper and most cop-

per alloys. The horizontal position is used in some fillet welding of corner joints and T-joints.

Vertical and overhead positions, and the horizontal position in welding butt joints, are infrequently used. They are ordinarily restricted to the gas tungsten-arc welding and gas metal-arc welding of aluminum bronzes, silicon bronzes and copper nickels. Small electrodes and filler-metal wire and low welding currents are used for out-of-position welding.

When using the shielded metal-arc process, out-of-position welding is usually limited to the joining of aluminum bronzes and copper nickels, but can also be done on phosphor bronzes and silicon bronzes.

Surface Condition. Grease and oxide on work surfaces should be removed before welding. Wire brushing or bright dipping can be used (see the article on Cleaning and Finishing of Copper and Copper Alloys, which begins on page 635 in Volume 2 of this Handbook).

Mill scale on the surfaces of aluminum bronzes and silicon bronzes is removed for a distance from the weld region of at least ½ in., usually by mechanical means.

Grease, paint, crayon marks, shop dirt and similar contaminants on copper nickels may cause embrittlement, and should be removed before welding. Mill scale on copper nickels must be removed by grinding or pickling; wire brushing is not effective.

Table 2. Filler Metals Most Frequently Used in Gas Tungsten-Arc Welding of Copper and Copper Alloys(a)

Filler metal	AWS classification	Principal constituents(b)
Copper	RCu	98.0 min Cu+Ag, 1.0 Sn, 0.5 Mn, 0.50 Si, 0.15 P
Phosphor bronze	RCuSn-A	93.5 min Cu + Ag, 4.0-6.0 Sn, 0.10-0.35 P
Phosphor bronze	ECuSn-C(c)	7.0-9.0 Sn, 0.05-0.35 P, rem Cu+Ag
Aluminum bronze	RCuAl-A2	1.5 Fe, 9.0-11.0 Al, rem Cu+Ag
Aluminum bronze	RCuAl-B	3.0-4.25 Fe, 11.0-12.0 Al, rem Cu+Ag
Silicon bronze	RCuSi-A	94.0 min Cu + Ag, 2.8-4.0 Si, 1.5 Zn, 1.5 Sn, 1.5 Mn, 0.5 Fe
Copper nickel	RCuNi	1.00 Mn, 0.40-0.70 Fe, 29.0-32.0 Ni+Co, 0.20-0.50 Ti, rem Cu+Ag

(a) Based on AWS A5.7 and A5.6; see current editions of those specifications for complete compositions and qualifications. (b) Single percentages are maximums unless otherwise stated. Optional elements and impurities have been omitted. (c) ECuSn-C is classified by AWS as electrode wire for gas metal-arc welding, but is used also as filler wire in gas tungsten-arc welding.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding is well suited for copper and copper alloys because of the intense arc, which produces an extremely high temperature at the joint, and a narrow heat-affected zone. In welding copper and the more heat-conductive copper alloys, the intensity of the arc is important in completing fusion with minimum heating of the surrounding, highly conductive base metal. In welding copper alloys that have been precipitation hardened, a narrow heat-affected zone is particularly desirable.

Gas tungsten-arc welding of copper and copper alloys is most frequently used for sections up to about ⅛ in. thick that have been prepared with a square edge. Often, no filler metal is used in joining these thicknesses. When sections over ⅛ in. thick are gas tungsten-arc welded, filler metal is almost always used (an exception is described in Example 326, in which ¼-in.-thick sections were gas tungsten-arc welded without the use of filler metal). Sections more than ½ in. thick are gas tungsten-arc welded only if gas metal-arc welding equipment is not available or if special conditions such as hot shortness of the base metal or adjacent heat-sensitive features make it necessary to limit the heat input.

Type of Current. Gas tungsten-arc welding is done on most copper and copper alloys with direct current, straight polarity (dcsp), to permit use of an electrode of minimum size for a given welding current and to provide maximum penetration.

Alternating current stabilized by high frequency is used on beryllium coppers and aluminum bronzes, to prevent the buildup of tenacious oxide films on these base metals.

Electrodes. Any of the standard tungsten or alloyed tungsten electrodes described on page 118 in the article on Gas Tungsten-Arc Welding can be used in gas tungsten-arc welding of copper and copper alloys, and the selection factors discussed in that article apply in general to these metals. Except as noted for specific classes of copper alloys, thoriated tungsten (usually EWTh-2) is preferred for its better performance, longer life and greater resistance to contamination.

Filler metals most frequently used in gas tungsten-arc welding of copper and copper alloys are listed in Table 2. Frequently, the filler-metal composition is matched closely to the base-metal composition, but a filler metal of composition different from that of the base metal may be selected. The reasons are dealt with in the discussions on gas tungsten-arc welding of the various copper alloys, throughout this article.

Mechanized Applications. One application of gas tungsten-arc welding of copper and copper alloys that is frequently mechanized to some degree is welding the ends of tubes into tube sheets. In the following example, a change from manual gas tungsten-arc welding to automatic welding, with mechanized equipment, increased production rate two to six times and improved quality for such welds.

Example 323. Change From Manual to Automatic Gas Tungsten-Arc Welding of Tubes to Tube Sheet (Table 3)

In the fabrication of heat exchangers and condensers, 0.048-in.-wall tubes ¾ in. in outside diameter of various copper alloys were automatically gas tungsten-arc welded to typically 1-in.-thick tube sheet of various other copper alloys (see Table 3).

Originally, the welds were made manually, but the operation was difficult and resulted in low productivity and questionable weld quality.

When processing was changed to automatic welding, joint strength equal to the minimum tensile strength of the base metals was usually attained, and production rates were two to six times as fast as in manual welding. Welding conditions, production rates and weld tensile strengths for automatic welding are shown in Table 3.

The joint was similar to that shown in Fig. 3 (for Example 330), consisting of a hole through the sheet, for insertion of the tube, with an 82° (included angle) countersink 0.040 in. deep on the face of the sheet, and with the tube end swaged outward into the countersink to lock it in place.

Equipment used in welding included a mandrel, which was inserted into the end of the tube, a welding torch, and rotary equipment that caused the electrode to trace a circle around the mandrel, and thus around the tube, when the control circuit was closed. The diameter of the welded circle could be adjusted to suit the workpiece.

In welding, controlled circuitry initiated a timed gas prepurge, and arc starting was by means of a high-frequency pulse. Welding was at full current around the 360° joint and an additional 20° overlap. A current decay was used to avoid crater cracks or pipes when the arc was broken.

Another application of mechanized gas tungsten-arc welding is butt joining the ends of small coils of metal strip, to make larger coils. The welding head traverses the length of the joint automatically. The use of this procedure for six alloys is described in the following example.

Example 324. Semiautomatic Gas Tungsten-Arc Welding To Join Strips of Alloy 110, 122, 210, 220, 230 or 260 (Table 4)

Strips 0.030 to 0.190 in. thick and up to 25 in. wide of alloy 110, 122, 210, 220, 230 or 260 were butt welded by the semiautomatic gas tungsten-arc process, under the conditions shown in Table 4, to make longer strips for cold reduction by rolling. Alloys 110, 122, 210, 220 and 230 were hard when welded; alloy 260 was soft.

The setup was similar to those shown in Fig. 4 (for Example 331), except that no shielding gas was fed through a backing groove. Filler metal was used only in welding the 0.190-in. strips of alloy 110 or 122.

The ends to be joined were cleaned of oxides and lubricants, sheared square simultaneously, butted together, and held flat with clamps. Tabs of the composition

Table 3. Welding Conditions, Production Rate and Tensile Strength for Automatic Gas Tungsten-Arc Welds Between Five Combinations of Copper Alloy Tube Sheet and Tube (Example 323)

(Welding with straight-polarity direct current, argon shielding gas at 15 cfh, and no filler metal)

Alloy numbers (and common names): Tube sheet(a)	Tube(b)	Current, amp	Welding time, sec	Production rate, welds/hr	Average tensile strength, psi
614 (aluminum bronze D)	687 (aluminum brass, arsenical)	160-170	16	80-85	50,800
655 (high-silicon bronze A)	122 (phosphorus-deoxidized, DHP)	170-180	12	90-100	34,300
655 (high-silicon bronze A)	442 (admiralty, not inhibited)	160-170	12	90-110	46,900
655 (high-silicon bronze A)	687 (aluminum brass, arsenical)	160-170	16	80-85	51,500
715 (copper nickel, 30%)	715 (copper nickel, 30%)	120-130	24	90-110	47,800

(a) Typically 1 in. thick, with holes (for the tubes) having 82° countersinks 0.040 in. deep. (b) ¾-in. outside diameter by 0.048-in. wall.

of the metal to be welded were placed under each end of the joint to control burn-through at the ends of the weld, and to be used for the arc to start and stop on. All joints were backed with a carbon block that had a groove ¼ in. wide by 1/64 in. deep cut into it directly beneath the joint. The electrode was ⅛-in.-diam EWTh-2. The torch nozzle was ½ in. in diameter. Helium shielding gas was used.

After welding, all of the alloys except alloy 260 were cold rolled to 25% reduction in cross section, annealed, and cold rolled again. Alloy 260 was cold rolled to 70 to 80% reduction before annealing.

None of the welds broke in rolling, although all of the brasses (alloys 210, 220, 230 and 260) fumed during welding and, as determined by examination of samples taken through the weld area, had some weld porosity.

Other uses of automation in gas tungsten-arc welding of copper and copper alloys are described in Examples 325, 326, 330 and 331.

Gas Tungsten-Arc Welding of Coppers

Although the weld quality of the commercial coppers joined by gas tungsten-arc welding differs depending on the cuprous oxide content of the copper, the nominal welding conditions for coppers of a given thickness and joint design are approximately the same (see Table 5).

Effect of Cuprous Oxide. Cuprous oxide present in the base metal or introduced through oxidation of the molten metal during the arc welding process migrates to the grain boundaries, thereby lowering the strength and ductility of the weld.

Best results in the arc welding of copper are obtained on deoxidized coppers, because (*a*) they are free from cuprous oxide, and (*b*) they contain residual phosphorus, which combines with oxygen absorbed during heating or welding, and thus prevents the formation of cuprous oxide. Strength, ductility and porosity of welds in alloy 102 (oxygen-free copper) are intermediate between the corresponding properties for welds in deoxidized coppers (alloys 120 and 122) and in alloy 110 (electrolytic tough pitch copper), which contains 0.02 to 0.05% oxygen.

The decrease in properties obtained by arc welding copper containing cuprous oxide is less than the decrease caused by gassing and embrittlement experienced in oxyacetylene welding of oxygen-bearing copper.

Shielding Gas. Argon is used typically in welding thicknesses of 1/16 or ⅛ in. In Example 325, an argon atmosphere was used in a closed chamber in welding a 1/16-in.-thick copper joint.

Helium or argon-helium mixtures are used in welding thicker workpieces, for which more heat input is needed. Helium and helium-rich mixtures with argon are used more often for copper than for most copper alloys because of the high thermal conductivity of copper and the consequent need for a high heat input. In Examples 324 and 326, helium shielding was used for welding 0.030 to ¼-in.-thick copper.

Gas-flow rate usually ranges from 15 to 40 cfh, being higher for the higher currents used in welding thicker sections (Table 5).

Table 4. Conditions for Semiautomatic Gas Tungsten-Arc Butt Welding Strips of Copper Alloys 110, 122, 210, 220, 230 and 260 (Example 324) (a)

Strip thickness, in.	Current (dcsp), amp	Voltage, v	Travel speed, ipm
Alloy 110 or 122			
0.030 to 0.035	80 to 95	20	50
0.080	230	21	40
0.190(b)	420 to 490	13 to 14	2
Alloy 210, 220 or 230			
0.030 to 0.035	80 to 95	20	50
Alloy 260			
0.090	180	17	35

(a) Strips of each alloy up to 25 in. wide, with ends cut with a shear set at 7° from the normal to the longitudinal direction, were welded with a square-edge butt joint, using an ⅛-in.-diam EWTh-2 electrode, a ½-in.-diam torch nozzle, helium shielding gas, and no filler metal (except for 0.190-in.-thick strips of alloy 110 or 122).

(b) A preheating pass with the torch was made at 4 in. per minute, by use of 200 amp and 18 to 20 v; a lithium-deoxidized copper filler wire was used in making the welding pass.

Type of Current. As indicated in Table 5, straight-polarity direct current is preferred for gas tungsten-arc welding of commercial coppers.

Electrodes. A thoriated tungsten electrode containing 2% thoria (EWTh-2) has the best electrode life and requires minimum tip maintenance in welding copper with straight-polarity direct current; EWTh-2 electrodes were used in Examples 324, 325 and 326, which deal with welding of copper alloys 110, 120 and 122.

Electrodes for use on copper are usually pointed, with a cone angle of 60°. The point on the tip is usually broken to a 0.005 to 0.020-in. flat.

Welding Without Filler Metal. Square-groove butt joints in copper up to ⅛ in. thick usually can be gas tungsten-arc welded without the use of filler metal, although filler metal is sometimes used in welding thicknesses close to ⅛ in. In Example 324, tough pitch and deoxidized coppers in thicknesses of 0.030 and 0.080 in. were welded without using filler metal; and in Example 325, no filler metal was used in making a shallow weld on an edge joint between two 1/32-in.-thick projections of deoxidized copper.

Copper in sections thicker than ⅛ in. can be gas tungsten-arc welded without the use of filler metal by making two passes, one from each side (as was done in joining ¼-in.-thick tough pitch copper in Example 326).

Filler metal is generally used in gas tungsten-arc welding of copper thicker than about ⅛ in. (Table 5). In Example 324, although no filler metal was used in butt welding copper 0.080 in. or less in thickness, a lithium-deoxidized copper filler wire was used on a thickness of 0.190 in.

The selection of a filler metal containing residual deoxidizer is important because of the adverse effects of oxygen on the dutility, strength and soundness of the weld metal (see discussion under "Effect of Cuprous Oxide", above). The adverse effects of oxygen are even more severe on the filler metal than on the base metal, because filler metal has greater exposure to welding heat.

Generally, copper filler metal that contains 0.15% max P and 0.50% max Si as deoxidizers (AWS RCu; see Table 2) is selected. Deoxidized coppers (alloys 120 and 122) as filler metal do not contain enough residual phosphorus to ensure sound welds. Other advantages of RCu filler metal are relatively high electrical conductivity (30 to 40% IACS) and good color match with the copper base metal.

Any of the other filler metals listed in Table 2 can be used in gas tungsten-arc welding of commercial coppers (because they contain adequate amounts of deoxidizing elements such as phosphorus, silicon, iron, aluminum or titanium), but electrical conductivity is limited and color match is poor. However, these filler metals provide greater joint strength.

Joint designs used in gas tungsten-arc welding of pure coppers as well as copper alloys are shown in Table 5. A root opening is required for welding butt joints in thicker sections with filler metal (see Table 5) because of the high thermal conductivity of copper. The clearance is needed to prevent the base metal from conducting heat away so rapidly that molten filler metal solidifies too quickly and chokes the joint before it is filled.

Backing strips or rings (usually made of copper, carbon or graphite) are ordinarily used in gas tungsten-arc welding of butt joints in copper, because of its high fluidity. Backing is needed for both tightly fitted butt joints in thin metal and loosely fitted butt joints in thick metal, to prevent loss of molten metal, and may also be used where needed for this purpose in making other types of joints.

Preheating. In gas tungsten-arc welding of sections thicker than ⅛ in., preheating is usually required, to maintain the base metal at welding temperature without excessive loss of heat to the surrounding area. The small arc used in gas tungsten-arc welding cannot maintain welding heat in thick sections of copper even under the most favorable conditions. Preheat temperatures are given in Table 5.

Deoxidized Coppers. Welded copper pressure vessels and other weldments that require the strength of the base metal are usually made from deoxidized copper.

Even with the localized heat input of gas tungsten-arc welding, special fixturing and other welding conditions may be needed to minimize distortion, as in the following example.

Example 325. Redesign of Joint and Fixture To Minimize Distortion in Gas Tungsten-Arc Welding of Alloy 120 (Fig. 1)

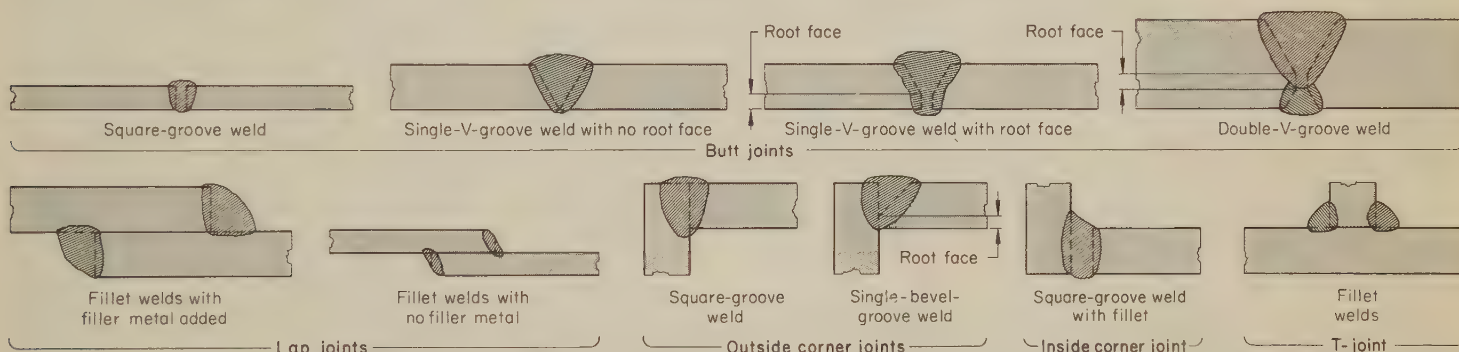
A wafer of nuclear fuel was encapsulated in an alloy 120 can-and-cover assembly by automatic gas tungsten-arc welding. The completed weldment is shown in Fig. 1(a). As shown in detail A in Fig. 1, the can had a machined recess for the wafer and a 0.005-in.-thick bottom. The can-to-cover joint had raised lips, which eliminated the need for filler metal.

The weld had to provide hermetic sealing without distorting the assembly, including the thin can bottom, which was only 3/16 in. from the welded area. Leak testing by a mass spectrometer was specified.

The welds were made in a controlled-atmosphere chamber, with the can mounted

Table 5. Nominal Conditions for Gas Tungsten-Arc Welding of Commercial Coppers(a)
(Using EWTh-2 electrodes, RCu welding rod, and straight-polarity direct current)

Work-metal thickness, in.	Root opening, in.(b)	Electrode diameter, in.	Diameter of welding rod, in.	Shielding gas(c)	Gas-flow rate, cfh	Current, amp	Travel speed, ipm	Number of passes	Preheat temperature, F
Butt Joints — Square Groove									
1/16	0	1/16	None used	Argon	15	110 to 140	12	1	None
1/8	0	3/32	None used	Argon	15	175 to 225	11	1	None
1/8	1/8	3/32	3/32, 1/8	Argon	15	175 to 225	11	1	None
3/16	3/16	1/8	1/8	Helium	30	190 to 225	10	1	200
Butt Joints — 60° Single-V Groove, 1/16-In. Root Face									
1/4	1/16 max	1/8	1/8	Helium	30	225 to 260	9	1	300
3/8	1/16 max	3/16	3/16	Helium	40	280 to 320	...	2	500
Butt Joints — 60° Double-V Groove, 1/8-In. Root Face(d)									
1/2	1/16 max	3/16, 1/4	1/4	Helium	40	375 to 525	...	3	500
Lap Joints — Fillet Welded(e)									
1/16	0	1/16	1/16	Argon	15	130 to 150	10	1	None
1/8	0	3/32	3/32, 1/8	Argon	15	200 to 250	9	1	None
3/16	0	1/8	1/8	Helium	30	205 to 250	8	1	200
1/4	0	1/8	1/8	Helium	30	250 to 280	7	1	300
3/8	0	3/16	3/16	Helium	40	300 to 340	...	3	500
Outside Corner Joints — Square Groove									
1/8	1/8 max	3/32	3/32, 1/8	Argon	15	175 to 225	11	1	None
3/16	3/16 max	1/8	1/8	Helium	30	190 to 225	10	1	200
1/4	3/16 max	1/8	1/8	Helium	30	225 to 260	9	1	300
3/8	1/4 max	3/16	3/16	Helium	40	280 to 320	...	2	500
Outside Corner Joints — 50° Single-Bevel Groove, 1/16-In. Root Face									
3/16	1/16 max	1/8	1/8	Helium	30	205 to 250	8	1	200
1/4	1/16 max	1/8	1/8	Helium	30	250 to 280	7	1	300
3/8	1/16 max	3/16	3/16	Helium	40	300 to 340	...	3	500
Inside Corner Joints — Square Groove, Fillet Welded									
1/8	1/8 max	3/32	3/32, 1/8	Argon	15	200 to 250	9	1	None
T-Joints — Fillet Welded									
1/8	1/16 max	3/32	3/32, 1/8	Argon	15	200 to 250	9	1	None
3/16	1/16 max	1/8	1/8	Helium	30	205 to 250	8	1	200
1/4	1/16 max	1/8	1/8	Helium	30	250 to 280	7	1	300
3/8	1/16 max	3/16	3/16	Helium	40	300 to 340	...	3	500



(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions, for welding of parts on which previous experience is lacking; they are subject to adjustments as necessary to meet the special requirements of individual applications. (b) Copper, carbon or graphite backing strips or rings may be used (see text). (c) Mixtures of argon and helium are also used (see text). (d) Depth of back V is 3/8 of stock thickness. (e) Use of filler metal optional for thicknesses of 1/4 in. or less.

in a rotating copper chill-block clamping fixture under a stationary electrode. Welding conditions are given in the table accompanying Fig. 1.

Originally, the fixture and joint shown in Fig. 1(b) and detail A (for original method) were used, but at currents high enough for fusion, the welds were porous, the welded joint leaked, and the can warped unacceptably.

The porosity that caused leaking resulted because, in machining of the can, lubricant was wiped into the surface of the metal by the cutting tool and subsequent cleaning failed to remove it. Machining without a lubricant eliminated the difficulty.

To minimize distortion, the joint and fixture were improved as follows:

1. The square lips of the joint were chamfered (40°) to a sharp edge, as shown in detail B (Improved method) in Fig. 1, to reduce the heat input necessary to make the weld. With the chamfered lips, the welding current could be lower because a smaller mass of metal was being melted at any instant.
2. The mass of the fixture was increased, as shown in Fig. 1(b), for improved method, to increase heat withdrawal. (The redesigned fixture also provided complete support for the thin can bottom against pressure during leak testing.)

Before welding, the assembly was retained in the fixture, which was held by a small chuck with all of the 0.005-in.-thick can bottom resting on the thick copper backing, as shown in the "improved method" view in Fig. 1(b) and in detail B. The fixtured assembly was welded in a chamber that was first vacuum-purged and then filled with 100% argon under slightly positive pressure.

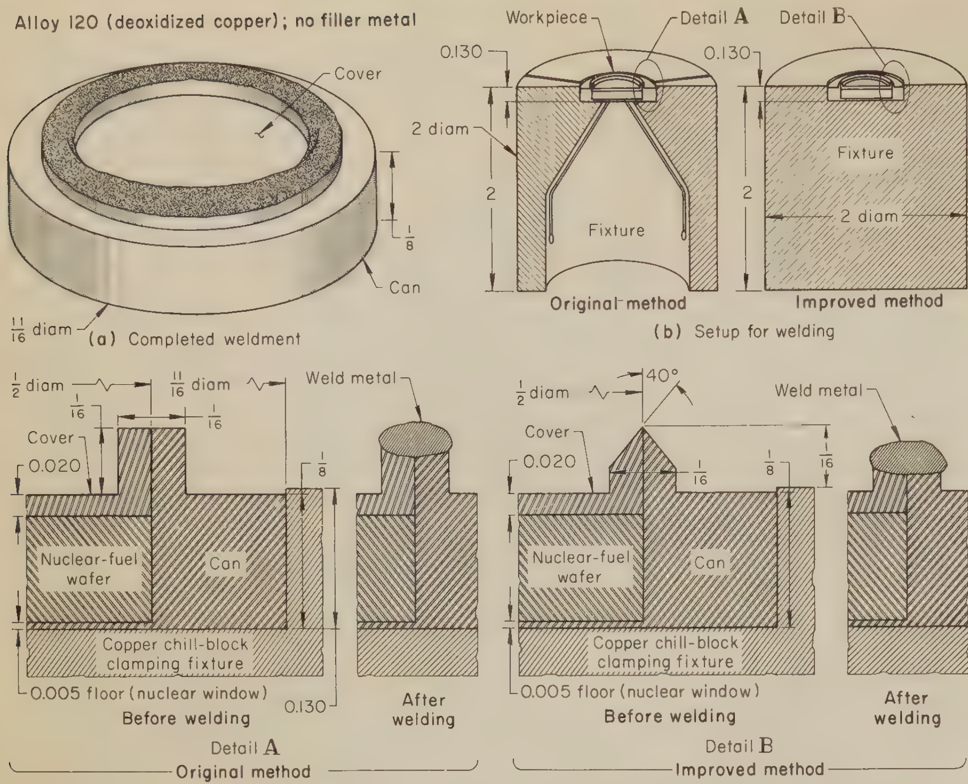
The torch was rigidly mounted on a sliding base with locating stops by which the electrode tip was positioned over the seam, and clamped in position. In the argon atmosphere it was not necessary to provide a shielding gas to the electrode tip or to use an electrode cup. The electrode was ground to a sharp point, to reduce currrent flow and to pinpoint the arc.

During welding, the chuck holding the fixture was rotated by a variable-speed drive. The arc was started, and arc stability was maintained, by a superimposed high-frequency current that was continuous. Current upslope was not controlled. Two revolutions, at 3½ rpm, were used, because slight variations in pressure between the cover and the can caused variations in the thickness of the weld bead after the first revolution. The second revolution smoothed out these irregularities, and ensured adequate penetration of the base metal along the circumference of the joint. After the second revolution, the current was tapered to zero in 5 sec.

Distortion was minimized because of the low welding current, the high heat-sink efficiency, and rigid support by the fixture. Control of heat input was also helpful in preventing excessive internal gas expansion after the joint was closed.

After welding, the welding chamber was evacuated to 10^{-6} torr. The interior of the can remained at approximately 15 psi. Under this pressure differential, the can, still in the fixture, was inspected for leaks by use of a mass spectrometer. The fixture supported the thin can bottom against internal pressure.

Oxygen-Free and Tough Pitch Coppers. Gas tungsten-arc welding is preferred to gas metal-arc welding, or



Automatic Gas Tungsten-Arc Welding

Joint type	Circumferential edge
Weld type	Edge flange
Power supply	250-amp rectifier
Electrode	0.040-in.-diam EWTh-2
Torch	110-amp, air cooled(a)
Filler metal	None
Fixture	(b)
Current	16 amp, dcsp(c)
Arc starting	(d)
Arc length	0.015 in.
Shielding gas	Argon(e)
Welding position	Flat
Travel speed	5.5 ipm

(a) Modified by elimination of ceramic cup, and by use of bare connecting cable to avoid the presence of organic material in the chamber.
(b) Copper chill-block clamping fixture held by a small chuck that was rotated by a variable-speed drive.
(c) With continuous superimposed high-frequency current, for arc stability. (d) Superimposed high-frequency current, which was continuous, as described in footnote (c). (e) In a vacuum-purged welding chamber; under slight positive pressure.

Fig. 1. Nuclear-fuel container for which distortion in welding was minimized by increasing mass of the fixture to increase heat withdrawal and by chamfering of joint edges to permit reduction of welding current (Example 325)

other processes generating less localized heat input, for joining either oxygen-free copper (alloy 102) or electrolytic tough pitch copper (alloy 110) in thicknesses up to about ½ in.

In Example 604, in the article on Resistance Brazing, automatic gas tungsten-arc welding was used in continuously welding the longitudinal seam in an ocean-cable inner conductor tube made of oxygen-free copper 0.023 in. thick. The close control of welding conditions obtainable with the process, and the use of a mixture of argon and helium as the shielding gas, provided electrode life of more than 100 hr before regrinding was required.

Gas tungsten-arc welds in alloy 102 (oxygen-free copper), because of the absence of a deoxidizer, have slightly lower strength and ductility, and are slightly more porous, than those in deoxidized coppers, unless all traces of oxygen are excluded.

Gas tungsten-arc welds in alloy 110 (electrolytic tough pitch copper) have somewhat lower tensile strength than that of welds in deoxidized coppers, and are more porous (see "Effect of Cuprous Oxide", page 340). However, the properties of gas tungsten-arc welds in electrolytic tough pitch copper (alloy 110) are acceptable in many applications involving welded electrical conductors — particularly when tensile strength is relatively unimportant, as for the induction-coil weldment described in the following example.

Example 326. Automatic Gas Tungsten-Arc Welding of 30-Ft Joints Between Alloy 110 Bar and Tubing (Fig. 2)

Alloy 110 solid bar 30 ft long was gas tungsten-arc welded automatically to a 30-ft length of alloy 110 tubing. The weldment was used in making water-cooled induction coils for low-frequency (60 to 180 Hz) induction heating that required more cross-sectional area for electrical conduction than was provided by the tubular section alone. Figure 2 shows a weldment with a cross section of typical size. The 30-ft length was standard for inductor stock. The weldment was bent into 4-in.-ID coils with the bar on the inside. The joint had to maintain good electrical conductivity.

Originally, the bar and tubing were torch brazed along the full length with a silver alloy filler metal. Not only was the filler metal expensive, but brazing was slow, needing two men to handle the 30-ft lengths of tubing and bar.

To increase production rate, a faster and less costly method was developed by mechanizing a gas tungsten-arc welding procedure in which no filler metal was used.

Welding conditions are given in the table accompanying Fig. 2. The fixture, which could accommodate the sizes of inductor bar and tubing regularly used, consisted of six guide rolls, as shown in Fig. 2, that properly aligned the assembly during welding. A chain and variable-speed drive were used to pull the assembly through the rolls during welding. The torch was on an adjustable mount that permitted it to be positioned over the joint to suit the size of components being welded.

Before welding, the leading end of the joint was brazed for about 1 in., to prepare the assembly for feeding through the guide rolls. The position of the assembly, guide rolls and electrode holder during welding is shown in Fig. 2. To make the weld, the assembly was pulled through the rolls at 13 in. per minute, as shown. One pass was used, without coolant, for each side, and the ends were trimmed after welding.

The high thermal conductivity of alloy 110 caused rapid dissipation of the heat energy. However, this difficulty was overcome without preheating by the use of helium as the shielding gas. Helium provided a hotter arc than could be obtained with argon. Thus, it was possible to produce relatively deep narrow welds at 13 in. per minute. Oxygen from the oxide in alloy 110 caused some porosity, but this was minimized by the fast freezing promoted by the fast travel speed. Thus required joint properties were obtained.

Gas Tungsten-Arc Welding of High-Conductivity Beryllium Copper

Gas tungsten-arc welding is preferred to other arc welding processes for joining precipitation-hardened alloy 175 (high-conductivity beryllium copper, 0.6% Be; composition as shown in Table 1) in thicknesses up to about ¼ in., because of the narrow heat-affected zone. The maximum thickness that can be gas tungsten-arc welded without substantial decrease in strength is about ½ in.; thicker workpieces are gas metal-arc welded (see Example 334). When heat treatment is required after welding, gas tungsten-arc welding generally is used only for thicknesses up to 0.090 in., and gas metal-arc welding for thicker sections.

Alloy 175 is more difficult to weld than alloys 170 and 172 (high-strength beryllium coppers), because of its higher thermal conductivity — which, for alloy 175 in the precipitation-hardened condition, is 53 to 66% that of tough pitch copper, or about twice that of high-strength beryllium coppers. A difficulty common to both high-conductivity and high-strength beryllium coppers is that of keeping the work surfaces free from beryllium oxide and cuprous oxide during welding.

Nominal conditions for gas tungsten-arc welding of alloy 175 are given in Table 6. The shielding gas is usually a mixture of argon and helium, to obtain a hot arc, smooth and spatter-free welds, and maximum electrode life.

Type of Current. Variation in arc length or welding speed during gas tungsten-arc welding can produce tenacious oxide films on beryllium copper. For this reason, high-frequency-stabilized alternating current, which continually breaks up the oxide coating, is preferred (see Table 6) in automatic welding, and must be used in manual welding. In automatic welding, advantage can sometimes be taken of the high heat input to the work and the deep penetration of straight-polarity

direct current, if close control is maintained over arc length and welding speed to minimize oxide formation.

Susceptibility to porosity and cracking is greater for welds made in high-conductivity than in high-strength beryllium copper, especially in multiple-pass welding. However, successfully welded joints show less effect on mechanical properties in the heat-affected zone than similar joints in high-strength beryllium copper.

Electrodes. The preferred electrode metal when using alternating current is zirconiated tungsten (EWZr); for economy, unalloyed tungsten (EWP) can be used in noncritical applications. Thoriated tungsten (such as EWTh-2) is preferred when straight-polarity direct current is used.

Filler metal of the same composition as the base metal (alloy 175) is generally used, because high electrical conductivity is usually desired in the welds. If maximum electrical conductivity across the joint is not a requirement, silicon bronze filler metal is satisfactory; aluminum bronze filler metals are usable, but less satisfactory.

Joint Design. As Table 6 indicates, the usual joint designs for gas tungsten-arc welding of high-conductivity beryllium copper are square-groove or 90° single-V-groove butt joints with 1/16-in. maximum root face, and no root opening. (See illustrations of joints in Table 5.) All joints should be backed with grooved copper or graphite backing strips or rings.

Preheating is not ordinarily needed for welding alloy 175 up to about 1/8 in. thick, but thicker stock (on which multiple-pass welds are used) is usually preheated to 800 F.

Gas Tungsten-Arc Welding of High-Strength Beryllium Coppers

High-strength beryllium coppers, alloys 170 (1.7% Be) and 172 (1.9% Be), are more easily welded than the higher-melting and less fluid high-conductivity beryllium copper.

Factors governing the suitability of gas tungsten-arc welding for high-strength beryllium copper are as described for high-conductivity beryllium copper. However, contrary to practice with the high-conductivity alloys, the gas tungsten-arc process can be used on thicknesses greater than 1/2 in. when it is not practical to weld by the preferred gas metal-arc process.

Nominal conditions, or suggested starting points, for gas tungsten-arc welding of high-strength beryllium coppers are given in Table 6. Shielding gas, type of current, and electrode type are the same as for alloy 175.

Filler metal is almost always used to fill the joint or to provide joint reinforcement in V-groove welds, because joint strength is of primary concern in welding these alloys. Rods or strips of the same composition as the base metal are generally used as filler metal; the standard filler metals of other copper alloys are weaker and offer no advantages.

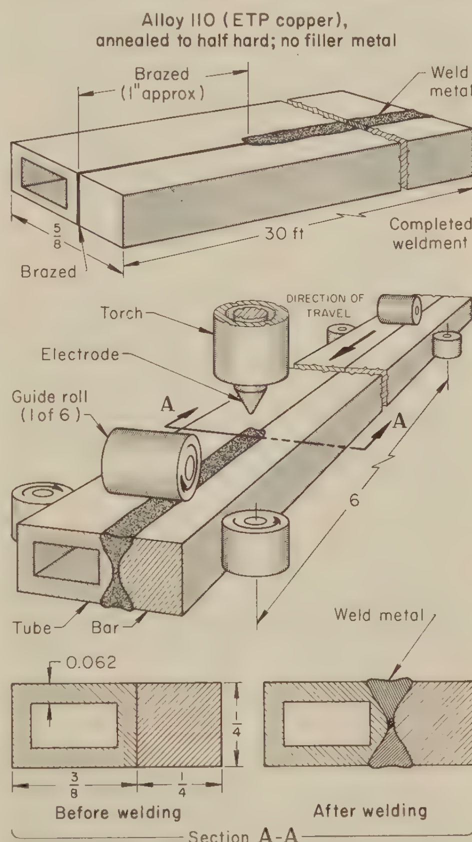
Joint design, which is indicated in Table 6, is the same as for high-conductivity beryllium copper. The 90° single-V-groove butt welds can be used for thicknesses greater than 1/2 in.

Table 6. Nominal Conditions for Gas Tungsten-Arc Welding of Beryllium Coppers(a)

(For butt joints having zero root opening; welding with a zirconiated tungsten electrode, filler metal of the same composition as the base metal, argon-helium shielding gas at 25 cfh)

Work-metal thickness, in.	Butt-joint groove(b)	Electrode diameter, in.	Current, amp(c)	Travel speed, ipm	Number of passes	Preheat temperature, F
Alloy 175 (High-Conductivity Beryllium Copper)(d)						
0 to 0.090	Square	3/32	150	5 to 10	1	None
0.090 to 1/8	90° single-V(e)	3/16	250	5 to 10	1 to 2	None
1/4	90° single-V(e)	3/16	250	5 to 10	4 to 5	800
Alloys 170 and 172 (High-Strength Beryllium Coppers)(d)						
0 to 0.090	Square	3/32	150	5 to 10	1	None
0.090 to 1/8	90° single-V(e)	3/32	180	5 to 10	1	None
1/4 to 1/2(f)	90° single-V(e)	3/16	250	5 to 10	3 to 4	300
Over 1/2(f)	90° single-V(e)	3/16	250	5 to 10	5 to 8	400

(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions for welding of parts for which previous experience is lacking; they are subject to adjustment as necessary to meet the special requirements of individual applications. (b) See Table 5 for illustrations of joints. (c) High-frequency-stabilized alternating current is preferred; straight-polarity direct current, with a thoriated tungsten electrode, is suitable under some conditions (see text). (d) For composition, see Table 1. (e) Maximum root face is 1/16 in. (f) Gas tungsten-arc welding is used on these thicknesses only when gas metal-arc welding cannot be used.



Automatic Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Square groove, zero root opening
Power supply	500-amp rectifier(a)
Electrode	1/8-in.-diam EWTh-2(b)
Torch	350-amp, water cooled(c)
Filler metal	None
Shielding gas	Helium, at 20 cfh
Fixture	Six guide rolls(d)
Current	220 amp, dcsp
Arc starting	Torch start
Arc length	1/8 in.
Cup-to-work distance	5/16 in.
Welding position	Flat
Number of passes	Two (one per side)
Welding speed	13 ipm
Preheat and postheat	None

(a) Constant-voltage. (b) Taper ground. (c) Fixed, on an adjustable mount. (d) Variable-speed drive and chain used to pull assembly through rolls.

Fig. 2. Alloy 110 tubing and bar, for inductor coils, that were automatic gas tungsten-arc welded, and position of assembly, guide rolls and torch during welding (Example 326)

Preheating and Postweld Heat Treatment. Preheating to 300 to 400 F is recommended for welding of metal thicker than 1/8 in. Maximum weld strength is obtained by solution annealing and aging after welding. Aging treatments are 3 hr at 600 F for alloy 170, and 3 hr at 650 F for alloy 172. However, even for welds made under optimum conditions, this postweld treatment does not consistently provide the full strength of solution annealed and aged base metal. Higher strength can be obtained by cold working the annealed metal to a higher temper and modifying the aging treatment.

For some applications, the intermediate weld-metal strength obtained by aging after welding, without solution annealing, is adequate; omission of solution annealing avoids the expense and distortion associated with that high-temperature operation.

Examples of Applications. Three applications of gas tungsten-arc welding of high-strength beryllium coppers are summarized in the grouped examples that follow.

Examples 327, 328 and 329. Gas Tungsten-Arc Welding of High-Strength Beryllium Coppers (Table 7)

Table 7 gives operating conditions for gas tungsten-arc welding of an alloy 170 pressure vessel (Example 327); a cylindrical generator liner for which alloy 170 was welded to alloy 172 (Example 328); and a cover, cast from a BeCu (1.7% Be) alloy, that was welded to an alloy 170 housing (Example 329).

The pressure vessel (Example 327) was used to scavenge propane from a Freon bubble chamber. Gas tungsten-arc welding was used because the vessel could not be solution annealed after welding, because of danger of warping. The service conditions for this vessel included pressure of 600 psi and rapid thermal cycling.

The cylindrical generator liner (Example 328) was back-extruded from a cast billet, and longitudinal ribs about 1/4 by 1/4 in. were machined on the outer surface. Nine reinforcing rings, 1 1/2 by 1 1/4 in., rolled from extruded alloy 170, were equally spaced along the ribs and welded to them. The liner, used in a magneto-hydrodynamic electrical power generator, contained plasma at 3000 to 3500 F.

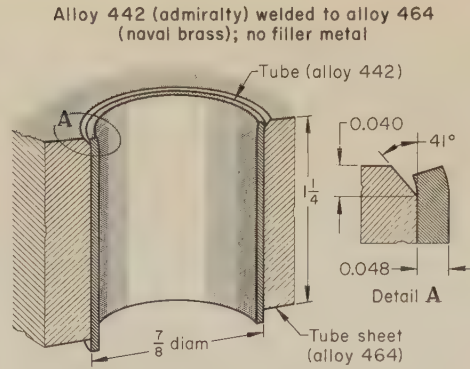
The cover-to-housing weldment (Example 329) was for ocean-cable use. The cast cover was welded to an extruded housing to provide a joint that was watertight at 12,000 psi.

Gas Tungsten-Arc Welding of Copper-Zinc Alloys

Of the copper-zinc alloys rated as to weldability in Table 1, the low-zinc brasses are shown to have good weldability by the gas tungsten-arc process. High-zinc brasses, tin brasses, special brasses and nickel silvers are shown to have only fair weldability, either because of high zinc content or because of moderate zinc content in combination with other elements, such as oxide-forming aluminum or nickel.

Gas tungsten-arc welding, because of its ability to weld rapidly with a highly localized heat input, is sometimes used for welding copper-zinc alloys (20% zinc or less) that contain up to 1% lead, even though leaded copper alloys are generally not recommended for arc welding.

Maximum thickness of copper-zinc alloys ordinarily gas tungsten-arc welded is about ⅜ in., although thick sections of cast alloys such as manganese bronze are sometimes repair welded in small local areas. Preheat is not ordinarily used in joining applications with these alloys.



Semiautomatic Gas Tungsten-Arc Welding

Joint type	Cylindrical edge
Weld type	Bevel
Electrode	⅛-in.-diam EWTh-2
Filler metal	None
Current	185 amp, dcsp
Voltage	(a)
Arc time	6 sec
Shielding gas	Argon, at 15 cfh
Welding speed	27.5 ipm

(a) Controlled by fixed arc length of 0.040 in.; no readings were taken.

Fig. 3. Joint preparation for welding a tube into a tube sheet by semiautomatic gas tungsten-arc welding (Example 330)

Shielding-gas selection is influenced by the heat requirements, which are related to the thermal conductivity of the base metal. Argon is commonly used for welding those alloys that are least conductive, whereas helium or helium mixtures are preferred for the alloys having greater conductivity. However, helium and helium-rich mixtures with argon are sometimes used on even the less conductive alloys (high-zinc brasses, tin brasses, special brasses and nickel silvers), to reduce zinc fumes.

Filler metals used in arc welding copper-zinc alloys should not contain zinc. The arc is struck and held on the filler metal rather than on the base metal, to help reduce zinc loss and fuming. RCuSn-A is recommended for the low-zinc brasses, and RCuSi-A for the high-zinc alloys.

The silicon in RCuSi-A helps to decrease zinc fumes. For this reason, and to provide joint reinforcement, RCuSi-A is sometimes used, with alternating current, on copper-zinc alloys 0.050 in. thick or less. RCuAl-A2 is sometimes used in welding the high-zinc alloys. It makes sound welds, but does not decrease zinc vaporization.

Welding Without Filler Metal. If filler metal is not used, high electrode travel speed will help to limit the amount of fuming by shortening total arc time. Tube-sheet joints similar to those described in Example 323 can be made with brass members using the same kind of joint preparation, if high electrode travel speed is maintained, as in the following example.

Example 330. Welding of Copper-Zinc Alloy Tube-Sheet Assemblies (Fig. 3)

Semiautomatic gas tungsten-arc welding was used to weld alloy 442 (admiralty) tubes to alloy 464 (naval brass) tube sheets as shown in Fig. 3. The tubes were ⅞ in. in outside diameter with 0.048-in. walls.

Linear speed of the welding electrode tip was 27.5 in. per minute, and each weld was completed in 6 sec.

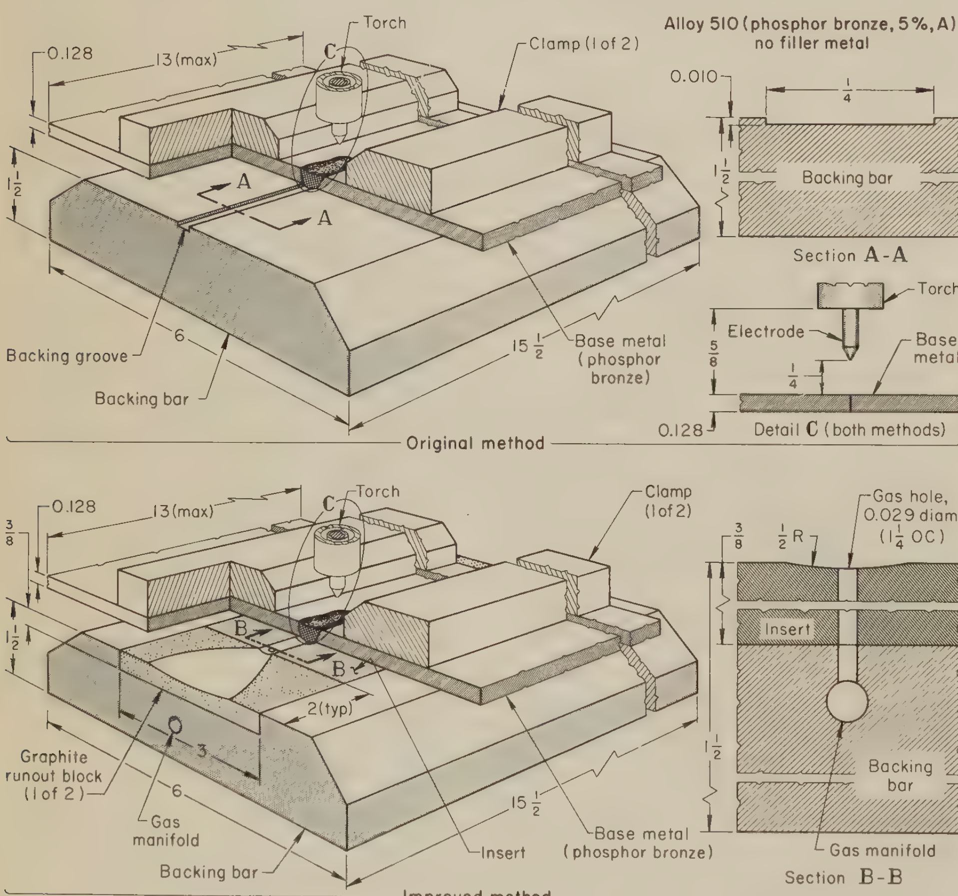
Although helium is the preferred shielding gas for this type of operation, argon was used successfully at a flow of 15 cu ft per hour. Some zinc fuming occurred when the welds were made, but the joints were uniformly sound and leakproof. Welding details are tabulated with Fig. 3.

Gas Tungsten-Arc Welding of Phosphor Bronzes

Gas tungsten-arc welding is used to join strip and other forms of wrought phosphor bronze up to about ½ in. thick. This process is also used to join or repair phosphor bronze castings.

Nominal conditions for gas tungsten-arc welding of square-groove butt joints in nonleaded phosphor bronzes are given in Table 8. The type of current used is straight-polarity direct current.

The nominal conditions shown in Table 8 are based primarily on the three phosphor bronzes shown in Table 1 to have low thermal conductivity (alloys 510, 521 and 524). Higher welding current or lower welding speed is needed for alloy 505 (phosphor bronze, 1.25% E), which contains 98.7% Cu and has three to four times the thermal conductivity of the three other alloys in this group.



Cost Data

Equipment	$75,000
Labor	2 operators at $2.95 and $3.57 per hour
Argon, 330-cu-ft tank	$19.00
Helium, 242-cu-ft tank	$17.00
Electric power	$0.012 per kwhr

Automatic Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	Square groove
Electrode	⅛ or 5⁄32-in.-diam EWTh-1; 18 in. long, pointed
Shielding gas	Helium, at 45 to 50 cfh
Backing gas	Argon, at 3 cfh
Filler metal	None
Voltage	15 to 18 v
Current	250 to 275 amp, dcsp
Power supply	400-amp three-phase rectifier
Arc start	Nontouch, high-frequency ac
Travel speed	30 to 40 ipm

Fig. 4. Setup for welding coil ends of phosphor bronze strip into lengths to be fed into a rolling mill, and details of design changes in backing bar (Example 331)

Shielding Gas. Argon is most often used because of the desirability of restricting the size of the heat-affected zone, thus minimizing the area where mechanical properties are decreased.

Helium shielding gas was used, along with an argon backup flow, in Example 331, and argon shielding gas was used in Example 332.

Filler Metal. RCuSn-A or wire of approximately the same composition as the base metal is ordinarily used as the filler metal. When matching the composition of the base metal is not essential, RCuSi-A filler metal can be used instead, with stronger welds.

Welding Without Filler Metal. If not thicker than about ⅛ in., phosphor bronze strip can be butt welded by the gas tungsten-arc process without the addition of filler metal, as in the application described in the next example.

Table 7. Three Applications of Gas Tungsten-Arc Welding of High-Strength Beryllium Coppers (Examples 327 to 329)

Item	Pressure vessel (Example 327)	Generator liner (Example 328)	Cover to housing (Example 329)
Alloy	170	170 to 172	Cast BeCu (1.7 Be) to 170
Size of workpiece, in.	19 diam by 40	19½ ID by 48	11.6 diam
Thickness of work metal, in.	¾	(a)	0.060
Filler metal	0.062-in.-diam alloy 172	None	None
Current, amp	100 to 150, dcsp	122, ac(b)	275 ac(b)
Shielding gas	Argon and helium	Argon and helium	Argon
Gas-flow rate, cu ft per hour	25	25	20
Travel speed, in. per minute	20	10	12
Number of passes	....	One	One
Postheat	650 F, 3 hr	None	None
Testing method	X-ray(c)	....	(d)

(a) Reinforcing rings, 1½ by 1¼ in., welded to ¼-in.-sq longitudinal ribs. (b) High-frequency-stabilized. (c) Weld was tested by dye-penetration techniques, leak testing by helium mass spectrometry, and x-ray radiography. (d) Weld depth (0.060 in., min) was determined ultrasonically; weld was leak tested by helium mass spectrometry at 11,000 psi of helium.

Table 8. Nominal Conditions for Gas Tungsten-Arc Welding of Square-Groove Butt Joints in Phosphor Bronzes(a)

Work-metal thickness, in.	Root opening, in.(b)	Electrode (EWTh-2) diameter, in.	Diameter of welding rod, in.(c)	Current (dcsp), amp	Flow rate of argon, cfh	Travel speed, ipm	Number of passes	Preheat temperature, F
0.012 to 1⁄16	0	⅛	None used	90 to 150	15 to 35	60 to 80	One	None
1⁄16 to ⅛	0 to 1⁄16	⅛	1⁄16 to 5⁄32	100 to 220	15 to 35	45 to 60	One	None

(a) Data here can serve as starting points in establishing optimum joint design and conditions for welding parts for which prior experience is lacking; they may be adjusted as necessary to meet the special requirements of individual applications. Higher current or lower welding speed is used in welding alloy 505 (see text). (b) See illustration of joint in Table 5. (c) RCuSn-A, or rod of composition close to that of the base metal.

Example 331. Gas Tungsten-Arc Welding of Phosphor Bronze Strip Without Filler Metal (Fig. 4)

Phosphor bronze strip of an alloy similar to 510 was reduced in a rolling mill from 0.128-in. thickness to 0.002-in. foil. The strip was delivered in coils that weighed up to 500 lb. For efficient handling, four coils were joined into one 2000-lb coil by butt welding the ends of the strip together as shown in Fig. 4 (detail C). The joints had to pass through the mill rolls with a minimum of interference, and to withstand reduction down to 0.002 in.

The joints were welded by the automatic gas tungsten-arc process in a machine that combined an uncoiler, a leveler, a shear, hydraulic clamps, electrode holder and travel carriage, and a recoiler. A 400-amp, three-phase rectifier and a 500-amp high-frequency oscillator were used.

The electrode (EWTh-1) was ⅛ or 5⁄32 in. in diameter and 18 in. long, and was ground to a point. No filler metal was used.

Some experimentation was necessary on the shape of the backing groove in the backing bar (compare "original method" and "improved method" views in Fig. 4). At first, a groove of rectangular cross section was used, to lie beneath the joint (section A-A in Fig. 4). Weld beads made with this backing groove were of generally rectangular shape and did not pass through the rolling mill easily. The backing bar was modified by changing the groove to a radiused cross section as shown in section B-B in Fig. 4. The change was made by mortising an insert into the original backing bar. The rounded weld bead produced when using this groove passed through the rolling mills without difficulty and withstood reduction to 0.002-in. thickness and elongation to 4 in.

Another improvement was to add gas holes 0.029 in. in diameter and spaced at 1¼-in. intervals along the groove to provide shielding gas for the back side of the weld. The groove was supplied with argon at 3 cu ft per hour from a manifold cut in the backing bar (see improved method, Fig. 4).

At the same time, graphite runout blocks were added at each end of the joint zone to prevent burnout at the edges of the strip (Fig. 4, improved method). This allowed subsequent use of the full width of the strip, without trimming, and thus increased productivity.

The coil-handling equipment, shear and clamps were operated manually. Arc start, arc length and torch travel were operated automatically. Approximately 120 welds were made in 8 hr.

Cost data and additional welding conditions are given in the table with Fig. 4.

Preheating is not normally used in gas tungsten-arc welding thin sections of the phosphor bronzes. Thick sections are usually preheated at 350 to 400 F, and are cooled slowly after welding. Because phosphor bronze is hot short, weld layers should be thin, and interpass temperature should not exceed 400 F. The weld can be hot peened to refine grain and minimize distortion.

In the example that follows, in which only partial penetration was necessary and high strength was not needed, 5⁄16-in.-thick phosphor bronze was gas tungsten-arc welded to ¾-in.-thick phosphor bronze without preheating and with peening of the weld being done after cooling.

Example 332. Gas Tungsten-Arc Welding of End-Cap Rings to Drilled Phosphor Bronze Bushings (Fig. 5)

A design change in heavy-duty bushings centrifugally cast in SAE 65 phosphor bronze (89 Cu, 11 Sn), called for gun drilling longitudinal holes that had to be end capped. End capping was done by gas tungsten-arc welding a flat ring, also cast from SAE 65 phosphor bronze, to each end of the bushing, as shown in Fig. 5.

Since the function of the weld was to maintain a close fit of the rings during the service life of the bushing, joint design called for only a partial-penetration, single-V-groove weld. This design caused distortion of the rings, because of unbalanced thermal stresses during welding, and constriction of the bushing diameter from shrinkage stresses after cooling.

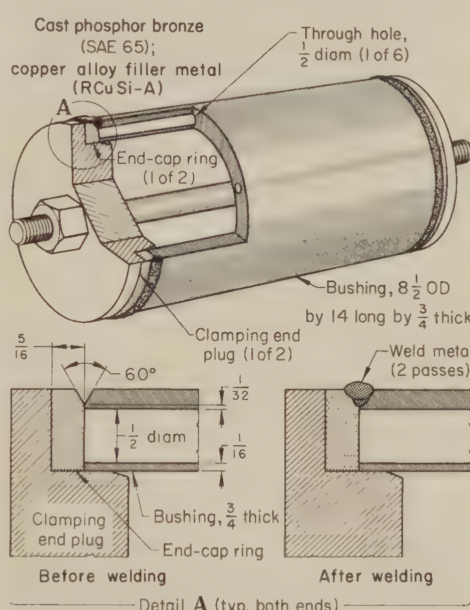
Both difficulties were overcome by designing a welding fixture consisting of a pair of flanged end plugs that could be drawn up tightly by means of a common threaded rod and nuts (Fig. 5). Machining the plugs for a close fit ensured accurate alignment of the parts during fit-up, welding, and cooling, and during subsequent peening. The plugs also served as a heat sink.

Gas tungsten-arc welding was done manually on the small quantities of bushings by rolling the bushing and its fixture on a steel-top table. A silicon bronze rod, RCuSi-A, was selected for filler metal for its weldability, strength, and color match. The shielding gas was argon.

The weld was made in two passes at approximately ½ rpm. Cracking from hot shortness was avoided by making relatively small weld deposits.

Before assembly, the semifinished machined parts were beveled by machining, and detergent cleaned. After cooling from welding, the welds were peened to relieve stresses, and examined visually and by liquid penetrants for porosity and cracks.

Other details of the welding operation are given in the table with Fig. 5.



Manual Gas Tungsten-Arc Welding

Joint type	Circumferential edge
Weld type	60° single-V groove (partial penetration)
Number of passes	Two
Power supply	250-amp rectifier
Electrode	1⁄16-in.-diam EWTh-2
Torch	250-amp, water cooled
Filler metal	1⁄16 or 3⁄32-in.-diam RCuSi-A
Shielding gas	Argon, at 10 to 12 cfh
Welding position	Horizontal rolled
Fixtures	Clamping end plugs
Current	130 amp, dcsp
Voltage	12 to 15 v
Arc starting	High open-circuit voltage (70 v)

Fig. 5. Heavy-duty bushing and setup for end-capping holes drilled longitudinally through the bushing wall (Example 332)

Table 9. Nominal Conditions for Gas Tungsten-Arc Welding of Aluminum Bronzes (a)
(For joint configurations, see Table 5)

Work-metal thickness, in.	Root opening, in.	Electrode diameter, in. (b)	Diameter of welding rod, in. (c)	Flow rate of argon, cfh	Current (ac, HF-stabilized), amp (d)	Number of passes
Square-Groove Butt Joints						
Up to 1/16	0	1/16	1/16 (e)	20 to 30	25 to 80	One
1/16 to 1/8	1/16 max	3/32	1/8	20 to 30	60 to 175	One
1/8	1/8 max	5/32 to 3/16	5/32	30	210	One
70° Single-V-Groove Butt Joints						
3/8	0	5/32 to 3/16	5/32	30	210 to 330	Four
Fillet-Welded T-Joints or Square-Groove Inside Corner Joints						
3/8	(f)	5/32 to 3/16	3/32	30	225	Three

(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions for welding parts on which previous experience is lacking; they are subject to adjustment as necessary to meet the special requirements of individual applications. Preheating is not ordinarily used in welding the thicknesses shown. (b) Zirconiated or unalloyed tungsten electrodes are recommended with high-frequency-stabilized alternating current. (c) Preferred welding rod is RCuAl-A2; otherwise, RCuAl-B or rod of the same composition as the base metal. (d) Straight-polarity direct current can also be used in making single-pass welds; see text. (e) Use of welding rod is optional for thicknesses up to 1/16 in. (f) Zero root opening for T-joints; 3/8 in. max for corner joints.

Gas Tungsten-Arc Welding of Aluminum Bronzes

Aluminum bronzes up to about 3/8 in. thick are readily joined by gas tungsten-arc welds, although welding conditions differ somewhat from those for most copper alloys. Porosity is minimized by the presence of iron, manganese or nickel in the filler metal or base metal, or in both. Aluminum bronze castings also are repair welded by gas tungsten-arc welding.

Nominal conditions for welding these alloys are given in Table 9.

Welding conditions are selected to avoid difficulties that may be caused by tenacious, refractory aluminum oxide coatings, which form almost instantaneously during any heating process such as welding unless oxygen is completely excluded. Heat input requirements are not high (aluminum bronzes have a thermal conductivity near that of carbon steel).

Shielding Gas. Argon permits adequate heat input and is used exclusively for gas tungsten-arc welding of aluminum bronzes.

The shielding effect of the gas is augmented, where necessary, by the use of a special flux applied to the edge of the joint to increase fluidity and to help protect the base metal from oxide formation. Aluminum oxide forms even at room temperature, and the flux prevents access of air to the prepared edges until the protective argon atmosphere becomes effective.

Type of Current. To prevent oxide buildup, alternating current stabilized by high frequency is preferred to straight-polarity direct current for gas tungsten-arc welding of aluminum bronzes. High-frequency-stabilized alternating current is particularly desirable in multiple-pass welding of these alloys.

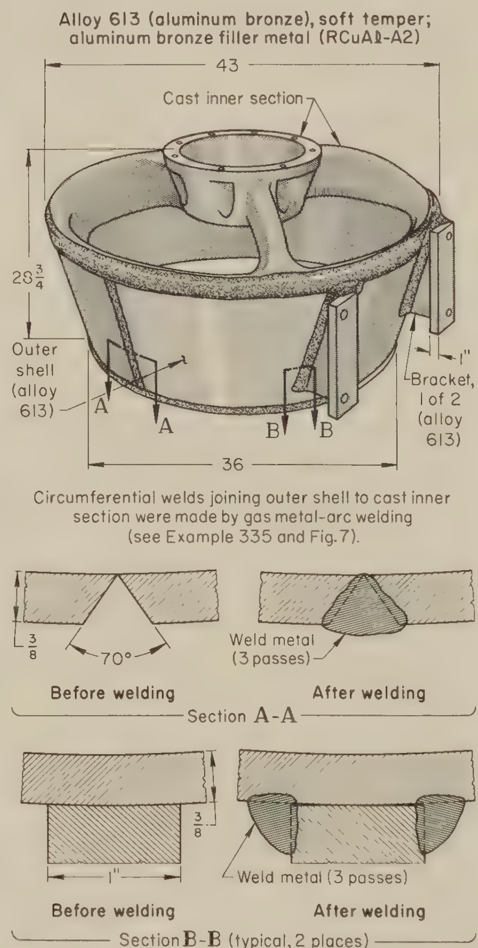
Straight-polarity direct current can be used in single-pass welding, particularly for automatic welding, when surfaces are well cleaned and protected and when the arc is closely controlled.

Electrodes for gas tungsten-arc welding of aluminum bronzes are usually zirconiated tungsten (EWZr) or unalloyed tungsten (EWP); thoriated tungsten electrodes cause the arc to wander when they are used with alternating current, although they may be used with direct current (Example 333). The electrode tip is flat, not tapered as in welding other copper alloys.

Filler metal RCuAl-A2 is ordinarily used. When a close match in composition and color with the base metal is needed, RCuAl-B or other aluminum bronze wire of a suitable composition should be used.

Preheating. Aluminum bronzes, which have relatively low thermal conductivity, do not usually need preheating for gas tungsten-arc welding of sections thinner than about 1/4 in. Preheating may be necessary in welding thicker sections, and was used in gas tungsten-arc welding 3/8-in.-thick aluminum bronze in Example 333. In contrast, no preheat was used in making gas metal-arc welds on the same assembly (Example 335).

Example of Application. Because gas tungsten-arc welding has a small, easily controlled arc, it is preferred to gas metal-arc welding for joining thin sections or where there is danger of damage from burn-through of adjacent surfaces, as in the following example.



Gas Tungsten-Arc Welding

Joint types .... Butt and T
Weld types .... Single-V groove and fillet
Welding position .... Flat
Number of passes .... Three
Power supply ...... 300-amp rectifier, constant-current type
Electrode 3/32-in.-diam EWTh-2
Torch .... Water cooled
Filler metal 3/32-in.-diam RCuAl-A2
Shielding gas .... Argon, at 15 to 20 cfh
Preheat and interpass temperature .... 300 F
Voltage .... 35 v
Current .... 225 amp, dcsp
Arc starting .... Contact and high frequency

Fig. 6. Propeller housing produced as an assembly welded by two processes. Weldment replaced a single-piece casting, reducing cost and improving serviceability. (Example 333)

Example 333. Use of Gas Tungsten-Arc Welding in Preference to Gas Metal-Arc Welding To Avoid Burn-Through of Neighboring Section (Fig. 6)

The propeller housing (Kort nozzle) shown in Fig. 6 had originally been made as a one-piece sand casting from aluminum bronze alloy 9B (ASTM B148), which contains 10% aluminum and 1% iron. However, difficulties experienced in the coring necessary to produce the thin outer shell led to the production of this outer shell as a separate piece that was welded to the casting to make a two-piece structure.

The inner section, faired to produce the most efficient flow from the propeller, was cast in propeller bronze, in one intricate piece that included an integral hub and shaft-mounting flange connected to the main body of the nozzle by four arms. The outer shell was cut from 3/8-in.-thick alloy 613 (aluminum bronze), soft temper, and was wrapped around the cast inner section after being cold formed into a truncated cone. Before cold forming, all edges of the shell were machined to a 35° bevel to provide a groove for subsequent welding.

The assembly was tack welded together, and then circumferential seams at the top and bottom were gas metal-arc welded, as described in Example 335. Then, to avoid burn-through of the faired cast inner section (and resultant poor effect on the propeller stream), gas tungsten-arc welding, under the conditions in the table with Fig. 6, was used for the longitudinal seam in the shell and for joining two alloy 613 brackets to the shell for mounting the housing to the hull of the vessel (Fig. 6).

Not only was the cost of production reduced by eliminating the complex and expensive coring in the casting, but the weight of the welded housing was less than that of the completely cast housing. Furthermore, the cast housing had been made of an alloy that (although easy to cast) did not resist erosion, corrosion and cavitation as well as did the alloys used in the welded assembly.

Gas Tungsten-Arc Welding of Silicon Bronzes

Gas tungsten-arc welding is used on thin to moderately thick nonleaded silicon bronzes, which are the most weldable of the copper alloys. One application of the process to these alloys is the welding of chemical-storage tanks,

for which smooth, clean, oxide-free welds can eliminate the need for grinding after welding. The welding of silicon bronze to other copper alloys and to copper is described in Example 323 and detailed in Table 3.

Nominal conditions for welding of silicon bronzes are given in Table 10. The data for manual welding include welding conditions for various positions. Because they have low fluidity, the silicon bronzes are the only group of copper alloys on which this process is applied extensively in the vertical and overhead positions.

The gas tungsten-arc welding of silicon bronze stock thinner than about 1/16 in. is best accomplished by using high-frequency-stabilized alternating current with zirconiated (EWZr) or unalloyed tungsten (EWP) electrodes.

Argon is used almost exclusively as the shielding gas for welding the silicon bronzes.

Filler Metals. The conventional silicon bronze filler metal, RCuSi-A, which is similar in composition to alloy 655 (high-silicon bronze A), the most commonly used silicon bronze, can be used to weld any of the silicon bronzes. Thin sections of silicon bronze can be gas tungsten-arc welded without the addition of filler metal, as described in Example 323.

Joint Design. On metal thicker than about 1/4 in., a V-groove with 60° included angle is used. Butt joints in thin stock can be welded without special preparation.

Preheating is not needed on silicon bronzes, some of which have lower thermal conductivity than do carbon steels (alloy 655, for instance). Further, because of the hot shortness of these alloys, preheating can be harmful, and interpass temperature on multiple-pass welds should not exceed 200 F.

Table 10. Nominal Conditions for Gas Tungsten-Arc Welding of Silicon Bronzes(a)

(Using zero root opening, no preheat, EWTh-2 electrodes, RCuSi-A welding rod, argon shielding gas, and straight-polarity direct current; for joint configurations, see Table 5)

Work-metal thickness, in.	Current, amp	Electrode diameter, in.	Travel speed, ipm	Diameter of welding rod, in.	Shielding-gas flow rate, cfh	Number of passes
AUTOMATIC WELDING						
Square-Groove Butt Joints, Flat Position						
0.012 to 0.050	80 to 140	1/8	60 to 80	None used	15 to 35	1
1/16 to 1/8	90 to 210	1/8	45 to 60	None used	15 to 35	1
1/8	250	1/8	18 to 20	1/16(b)	15 to 35	1
MANUAL WELDING						
Square-Groove Butt Joints, Flat Position						
1/16	100 to 120	1/16	12	1/16	15	1
1/8	130 to 150	1/16	12	3/32	15	1
3/16	150 to 200	3/32	...	1/8	20	1
1/4	250 to 300	1/8	...	1/8, 3/16	20	1
1/4	150 to 200	3/32	...	1/8, 3/16	20	3
Square-Groove Butt Joints, Vertical and Overhead Positions						
1/16	90 to 110	1/16	...	1/16	15	1
1/8	120 to 140	1/16	...	3/32	15	1
60° Single-V-Groove Butt Joints, Flat Position						
3/8	230 to 280	1/8	...	1/8, 3/16	20	3 to 4
1/2	250 to 300	1/8	...	1/8, 3/16	20	4 to 5
3/4(c)	300 to 350	1/8	...	3/16	20	9 to 10
1(c)	300 to 350	1/8	...	3/16, 1/4	20	13
Fillet-Welded Lap Joints, Flat Position						
1/16	110 to 130	1/16	10	1/16	15	1
1/8	140 to 160	1/16, 3/32	10	3/32	15	1
3/16	175 to 225	3/32	...	1/8	20	1
1/4	175 to 225	3/32	...	1/8, 3/16	20	3
3/8	250 to 300	1/8	...	1/8, 3/16	20	3
1/2	275 to 325	1/8	...	1/8, 3/16	20	6
3/4(c)	300 to 350	1/8	...	3/16	20	12
1(c)	325 to 350	1/8	...	1/4	20	16
Fillet-Welded Lap Joints, Vertical and Overhead Positions						
1/16	100 to 120	1/16	...	1/16	15	1
1/8	130 to 150	1/16, 3/32	...	3/32	15	1
Square-Groove Outside Corner Joints, Flat Position						
1/16	100 to 130	1/16	12	1/16	15	1
1/8	130 to 150	1/16	12	3/32	15	1
3/16	150 to 200	3/32	...	1/8	20	1
Square-Groove Outside Corner Joints, Vertical and Overhead Positions						
1/16	90 to 110	1/16	...	1/16	15	1
1/8	120 to 140	1/16	...	3/32	15	1
50° Single-Bevel-Groove Outside Corner Joints, Flat Position(d)						
1/4	175 to 225	3/32	...	1/8, 3/16	20	3
3/8	230 to 280	1/8	...	1/8, 3/16	20	3
1/2	275 to 325	1/8	...	1/8, 3/16	20	7
3/4(c)	300 to 350	1/8	...	3/16	20	14
1(c)	325 to 350	1/8	...	3/16, 1/4	20	20
Fillet-Welded Square-Groove Inside Corner Joints, Flat Position(e)						
1/16	110 to 130	1/16	10	1/16	15	1
1/8	140 to 150	1/16, 3/32	10	3/32	15	1
3/16	175 to 225	3/32	...	1/8	20	1
Fillet-Welded T-Joints, Flat Position						
1/16	110 to 130	1/16	10	1/16	15	1
1/8	140 to 160	1/16, 3/32	10	3/32	15	1
3/16	175 to 225	3/32	...	1/8	20	1
1/4	175 to 225	3/32	...	1/8, 3/16	20	3
3/8	230 to 280	1/8	...	1/8, 3/16	20	3
1/2	275 to 325	1/8	...	1/8, 3/16	20	7
3/4(c)	300 to 350	1/8	...	3/16	20	14
1(c)	325 to 350	1/8	...	3/16, 1/4	20	20

(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions for welding parts on which previous experience is lacking; they are subject to adjustment as necessary to meet the special requirements of individual applications. (b) Wire-feed rate, 115 to 125 in. per minute. (c) Thicknesses greater than about 1/2 in. are gas tungsten-arc welded only when it is not practicable to use gas metal-arc welding. (d) Root face is 1/16 in. for thicknesses of 1/2 in. or less, and 1/8 in. for thicknesses greater than 1/2 in. (e) Maximum root opening = t (work-metal thickness).

Gas Tungsten-Arc Welding of Copper Nickels

Gas tungsten-arc welding is the preferred process for joining copper nickels in thicknesses up to about 1/16 in. and may be used for greater thicknesses. Data on the automatic welding of alloy 715 (copper nickel, 30%) tubes to tube sheets of the same alloy are given in Table 3 for the welding operations described in Example 323.

Nominal conditions for automatic and manual gas tungsten-arc welding of the most common copper-nickel alloys are given in Table 11, for butt joints with square and single-V grooves.

Preferred conditions include the use of argon shielding gas, straight-polarity direct current, and thoriated tungsten electrodes, although these variables are not critical for copper nickels, because these alloys have low heat conductivity.

Current is slightly higher for alloy 706 (as shown in Table 11), because of its higher thermal conductivity; or a slower welding speed can be used. Preheating is not needed.

Backing strips or rings for use in welding copper nickels should not be made from carbon, graphite or steel; instead, copper or copper-nickel backing should be used.

Filler Metal. The only filler-metal composition ordinarily used in gas tungsten-arc welding of copper nickels is RCuNi. This filler metal contains 0.20 to 0.50% Ti to minimize porosity and the possibility of oxygen embrittlement, either in the weld metal or in the heat-affected zone, by acting as a deoxidizer.

Because the standard copper-nickel alloys do not contain titanium or a comparable deoxidizer, filler metal should be used, even in welding thin sheet of copper nickels, to avoid porosity. However, special compositions of alloys 706 and 715 that contain titanium are available, and thin sheet of these special alloys can be welded without the use of filler metal.

In multiple-pass welding, the welding-rod size and current may be increased with successive passes, as shown in Table 11, for the most efficient deposition rate.

Table 11. Nominal Conditions for Gas Tungsten-Arc Butt Welding of Copper Nickels(a)

Work-metal thickness, in.	Butt-joint groove(b)	Current (dcsp), amp	Electrode diameter, in.(c)	Travel speed, ipm	Diameter of RCuNi welding rod, in.(d)	Flow rate of argon, cfh	Number of passes
Automatic Welding of Alloy 706 (Copper Nickel, 10%)							
1/8	Square	310 to 320	3/16	15 to 18	1/16	25-30	1
Manual Welding of Alloy 706 (Copper Nickel, 10%)							
0 to 1/8	Square	300 to 310	3/16	5	1/8	25-30	1
1/8 to 3/8	70-80° single-V	300 to 310(e)	3/16	6	1/8, 3/16	25-30	2 to 4
Manual Welding of Alloy 715 (Copper Nickel, 30%)							
0 to 1/8	Square	270 to 290	3/16	5	1/8	25-30	1
1/8 to 3/8	70-80° single-V	270 to 290(e)	3/16	6	5/32	25-30	4

(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions for welding parts on which previous experience is lacking; they are subject to adjustment as necessary to meet the special requirements of individual applications. Root opening is zero. Preheating is not needed. (b) See Table 5 for illustrations of joints. (c) Preferred electrode material is EWTh-2. (d) Filler metal (RCuNi) must be used on all welded joints; see text. (e) Current should be increased in equal increments with each pass, up to a maximum of about 375 amp, with larger welding rods.

Table 12. Filler Metals and Preheat and Interpass Temperatures Used in Gas Tungsten-Arc Welding of Coppers and Copper Alloys to Dissimilar Metals(a)

One metal to be welded	Filler metals (and preheat and interpass temperatures) for welding metal in column 1 to: Coppers	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels
Copper Alloys					
Low-zinc brasses	ECuSn-C(b) or RCu (1000 F)	....	....	....	....
Phosphor bronzes	ECuSn-C(b) or RCu (1000 F)	....	....	....	....
Aluminum bronzes	RCuAl-A2 (1000 F)	RCuAl-A2 or ECuSn-C(b) (400 F)	....	....	....
Silicon bronzes	ECuSn-C(b) or RCu (1000 F)	RCuSi-A (150 F max)	RCuAl-A2 (150 F max)	....	....
Copper nickels	RCuAl-A2 or RCu or RCuNi (1000 F)	ECuSn-C(b) (150 F max)	RCuAl-A2 (150 F max)	RCuAl-A2 (150 F max)	....
Nickel Alloys					
Nickel and Ni-Cu alloys	RCuNi or ERNiCu-7 (1000 F)	(c)	(c)	(c)	RCuNi or ERNiCu-7 (150 F max)
Ni-Cr, Ni-Fe and Ni-Cr-Fe alloys	ERNi-3 (1000 F)	(c)	(c)	(c)	ERNi-3 (150 F max)
Steels					
Low-carbon steel	RCuAl-A2 or RCu or ERNi-3 (1000 F)	ECuSn-C(b) (400 F)	RCuAl-A2 (300 F)	RCuAl-A2 (150 F max)	RCuAl-A2 or ERNi-3 (150 F max)
Medium-carbon steel	RCuAl-A2 or RCu or ERNi-3 (1000 F)	ECuSn-C(b) (400 F)	RCuAl-A2 (400 F)	RCuAl-A2 (150 F max)	RCuAl-A2 or ERNi-3 (150 F max)
High-carbon steel	RCuAl-A2 or RCu or ERNi-3 (1000 F)	ECuSn-C(b) (500 F)	RCuAl-A2 (500 F)	RCuAl-A2 (400 F)	RCuAl-A2 or ERNi-3 (150 F max)
Low-alloy steel	RCuAl-A2 or RCu or ERNi-3 (1000 F)	ECuSn-C(b) (500 F)	RCuAl-A2 (500 F)	RCuAl-A2 (400 F)	RCuAl-A2 or ERNi-3 (150 F max)
Stainless steel	RCuAl-A2 or RCu or ERNi-3 (1000 F)	ECuSn-C(b) (400 F)	RCuAl-A2 (150 F max)	RCuAl-A2 (150 F max)	RCuAl-A2 or ERNi-3 (150 F max)
Cast Irons					
Gray and malleable irons	RCuAl-A2 or RCu (1000 F)	ECuSn-C(b) (400 F)	RCuAl-A2 (400 F)	RCuAl-A2 or RCuSi-A (300 F)	RCuAl-A2 (150 F max)
Ductile iron	RCuAl-A2 or RCu (1000 F)	ECuSn-C(b) (400 F)	RCuAl-A2 (150 F max)	RCuAl-A2 or RCuSi-A (150 F max)	RCuAl-A2 (150 F max)

(a) Filler-metal selections shown in table are based on weldability, except where mechanical properties are usually more important. Preheating is ordinarily used only when at least one member is thicker than about 1/8 in. or is highly conductive (see text). Preheat and interpass temperatures are subject to adjustment on the basis of the size and shape of the weldment. (b) ECuSn-C is classified by AWS as an electrode wire for gas metal-arc welding, but is used also as filler wire in gas tungsten-arc welding. (c) These combinations of work metals are only infrequently joined by welding; as a starting point in developing welding procedures for joining them, the use of RCuAl-A2 filler metal is recommended, except for welding of combinations that include phosphor bronzes.

Gas Tungsten-Arc Welding of Dissimilar Metals

Copper and many copper alloys can be gas tungsten-arc welded to other copper alloys, steels, stainless steels, and nickel and nickel alloys — usually with the aid of a filler metal. Because the use of gas tungsten-arc welding for this purpose is usually restricted to thin metal, the welding is ordinarily done without "buttering" with a preliminary surfacing weld. Combinations of dissimilar metals in thicknesses greater than about 1/8 in. are preferably joined by gas metal-arc welding or, where gas metal-arc welding is not applicable, by shielded metal-arc welding.

Usually, the arc is directed at the more conductive metal of the combination being welded.

Welding With Filler Metal. Table 12 shows combinations of dissimilar metals that are joined by gas tungsten-arc welding with the aid of copper alloy or nickel alloy filler metals, and gives the recommended filler metals and preheat and interpass temperatures for each combination.

Nearly all of the weldable copper alloys, as listed in Table 1, can be joined to dissimilar metals in this way. Copper-zinc alloys are not gas tungsten-arc welded to dissimilar metals, except for the welding of copper to low-zinc brass, which is done with phosphor bronze filler metal.

Ordinarily, joints between a ferrous metal and copper or a copper alloy by this method are welds on the copper side of the joint and braze welds on the iron side of the joint, because the melting point of the filler metal is lower than that of the base metal. Exceptions are gas tungsten-arc welds joining a copper or a copper nickel to a ferrous metal, using the nickel filler metal ERNi-3, as listed in Table 12. These are true welds on both sides of the joint.

The aluminum bronze filler rod RCuAl-A2 is compatible with most of the metals in Table 12, with the notable exception of the phosphor bronzes, and is by far the most widely used filler metal for gas tungsten-arc welding the dissimilar metals shown. Unlike copper, phosphor bronze and silicon bronze filler metals, RCuAl-A2 can tolerate substantial amounts of dilution with iron, and thus can be used for joining ferrous metals to copper alloys with minimum danger of cracking.

Preheating. Except where one or both members of a joint have high thermal conductivity, preheating is not needed for welding the dissimilar metals listed in Table 12 if both members are less than about 1/8 in. thick.

Referring to Table 12, in most cases the lower preheat temperature or an intermediate temperature applies when two alloys that have different preheat requirements are welded together. An exception is the joining of copper to other metals, in which the need to provide enough heat in this highly conductive metal overrides other considerations, and the preheat temperature of 1000 F shown for copper must be used to ensure successful welds.

Table 13. Nominal Conditions for Gas Metal-Arc Butt Welding of Commercial Coppers and Copper Alloys(a)

Weld types for butt joints (see Table 5 for illustrations)	Work-metal thickness, in.	Root face, in.	Root opening, in.	Electrode	Electrode-wire diameter, in.	Shielding gas	Gas-flow rate, cfh	Current (dcrp), amp	Voltage, v	Travel speed, ipm	Number of passes	Preheat temperature, F
Commercial Coppers												
Square groove(b)	⅛	⅛	0	ECu	1/16	Argon	30	310	27	30	1	None
Square groove(c)	⅛	⅛	0-1/16	ECu	1/16	Argon(d)	30-35	325-350	28-33	...	1	None
Square groove	¼	¼	0	ECu	3/32	Argon	30	460	26	20	2	200
	¼	¼	0	ECu	3/32	Argon	30	500	27	20	1	200
75-90° single-V groove(c)	¼	⅛	0-⅛	ECu	1/16	Argon(d)	30-35	400-425	32-36	...	2	400-500
	½	0-⅛	0-⅛	ECu	1/16	Argon(d)	30-35	425-450	35-40	...	4	800-900
90° single-V groove	⅜	3/16	0	ECu	3/32	Argon	30	500	27	14	(e)	400
	⅜	3/16	0	ECu	3/32	Argon	30	550	27	14	(e)	400
	½	¼	0	ECu	3/32	Argon	30	540	27	12	(e)	400
	½	¼	0	ECu	3/32	Argon	30	600	27	10	(e)	400
Alloy 175 (High-Conductivity Beryllium Copper)(f)												
90° single-V groove	¼-½	1/32	...	Alloy 175	0.045	A-He	30	200-240	...	...	3-4(g)	600
	¾	1/32	...	Alloy 175	0.045	A-He	30	200-240	...	...	6(g)	900
Alloys 170 and 172 (High-Strength Beryllium Coppers)(f)												
90° single-V groove	¼-½	1/32-1/16	...	Alloy 170, 172	0.045	A-He	45	175-200	...	...	3-4(h)	300-400
30° double-U groove(j)	¾-1½	1/16	...	Alloy 170, 172	1/16	A-He	60	325-350	...	...	10-20(k)	300-400
Low-Zinc Brasses												
Square groove(c)	⅛	⅛	0	ECuSi	1/16	Argon	30	275-285	25-28	...	1	None
	⅛	⅛	0	ECuSn-C	1/16	Helium	35	275-285	25-28	...	1	None
60° single-V groove(c)	⅜	0	⅛	ECuSi	1/16	Argon	30	275-285	25-28	...	2	None
	½	0	⅛	ECuSi	1/16	Argon	30	275-285	25-28	...	4	None
70° single-V groove(c)	⅜	0	⅛	ECuSn-C	1/16	Helium	35	275-285	25-28	...	2	500(m)
	½	0	⅛	ECuSn-C	1/16	Helium	35	275-285	25-28	...	4	500(m)
High-Zinc Brasses, Tin Brasses, Special Brasses, Nickel Silvers												
Square groove(c)	⅛	⅛	0	ECuSn-C	1/16	Argon	30	275-285	25-28	...	1	None
70° single-V groove(c)	⅜	0	⅛	ECuSn-C	1/16	Argon	30	275-285	25-28	...	2	None
	½	0	⅛	ECuSn-C	1/16	Argon	30	275-285	25-28	...	4	None
Phosphor Bronzes(n)												
90° single-V groove(c)	⅜	0	⅛	ECuSn-A(p)	1/16	Helium	35	275-285	25-28	...	3-4(q)	200-300
	½	0	⅛	ECuSn-A(p)	1/16	Helium	35	275-285	25-28	...	5-6(q)	350-400
Aluminum Bronzes(r)												
Square groove(s)	⅛	⅛	0	ECuAl-A2	1/16	Argon	30	280-290	27-30	...	1	None
60-70° single-V groove(c)	⅜	0	⅛	ECuAl-A2	1/16	Argon	30	280-290	27-30	...	2	None
	½	0	⅛	ECuAl-A2	1/16	Argon	30	280-290	27-30	...	3	Slight
Silicon Bronzes(t)												
Square groove(u)	⅛	⅛	0	ECuSi	1/16	Argon	30	260-270	27-30	8 min	1	None
60° single-V groove(c)	⅜	0	⅛	ECuSi	1/16	Argon	30	260-270	27-30	8 min	2	None
	½	0	⅛	ECuSi	1/16	Argon	30	260-270	27-30	8 min	3	None
Copper Nickels												
Square groove(c)	⅛	⅛	0	ECuNi	1/16	Argon	30	280	27-30	...	1	None
60-80° single-V groove(c)	⅜	0-1/32	⅛-¼	ECuNi	1/16	Argon	30	280	27-30	...	2	None
	½	0-1/32	⅛-¼	ECuNi	1/16	Argon	30	280	27-30	...	4	None
Commercial Coppers to Steel												
70-80° single-V groove	⅜	1/16	⅛	ERNi-3	1/16	Argon	60	375	29-31	...	4	800-1000
Copper Nickel to Steel												
70-80° single-V groove	⅜	1/16	⅛	ERNi-3	1/16	Argon	60	375	29-31	...	4	150 max
Aluminum Bronze to Steel(v)												
60° single-V groove	⅜	0	5/16-⅜	ECuAl-A2	1/16	Argon	30	270-280	25-27	...	6	300-500
Silicon Bronze to Steel(w)												
60° single-V groove	⅜	0	5/16-⅜	ECuAl-A2	1/16	Argon	30	270-280	28-30	...	6	150 max(x)

(a) The data in this table are intended to serve as starting points for the establishment of optimum joint design and conditions for welding of parts on which previous experience is lacking; they are subject to adjustment necessary to meet the requirements of individual applications. Thicknesses up to about 1½ in. are sometimes welded, by use of slightly higher current and lower travel speed than shown for a thickness of ½ in. (b) Copper backing. (c) Grooved copper backing. (d) Or 75% argon, 25% helium. (e) Special welding sequence is used; see text.
(f) See Table 1 for compositions. (g) The final pass is made on the root side after back chipping. Grind after each pass. (h) The final pass is made on the root side after back chipping. Wire brush after each pass. (j) Similar to the double-V-groove weld shown in Table 5, but with a groove radius of ⅜ in. (k) Several passes are made on the face side, then several on the back side, until the weld is completed. Back chip the root pass before making the first pass on the back side. Wire brush after each pass. (m) Should not be overheated; as little preheat as possible should be used. (n) Welding conditions based on alloys 510, 521 and 524; current is increased or speed decreased for alloy 505.
(p) Or ECuSn-C. (q) Hot peening between passes is recommended for maximum strength. (r) Slight preheat may be needed on heavy sections; interpass temperature should not exceed 600 F. (s) With ⅛-by-1-in. aluminum bronze backing. (t) No preheat is used on any thickness; interpass temperature should not exceed 200 F. (u) With ⅛-by-1-in. silicon bronze backing. (v) Steel should be well penetrated; an overlay is not usually needed. (w) Steel should be well penetrated; an overlay should be applied to avoid excessive dilution of the silicon bronze. (x) Except in welding silicon bronze to high-carbon or low-alloy steel, for which preheat temperature is 400 F.

Interpass temperatures should not ordinarily be allowed to rise above the prescribed preheat temperature, because many of the copper alloys are hot short at higher temperatures.

Welding Without Filler Metal. Certain combinations of copper alloys, usually not differing widely in composition, can be gas tungsten-arc welded in thicknesses up to about ⅛ in. without filler metal.

Examples 323 and 330 describe the gas tungsten-arc welding of several combinations of dissimilar copper alloys without the use of filler metal.

Gas Metal-Arc Welding

Gas metal-arc welding is used to join all of the coppers and copper alloys listed in Table 1. It is preferred for joining the aluminum bronzes, silicon bronzes and copper nickels in section thicknesses greater than about ⅛ in. (Gas tungsten-arc welding is preferred for thicknesses less than about ⅛ in.)

The major application of gas metal-arc welding to copper alloys is in joining material from ⅛ to ½ in. thick, and the process is almost invariably selected for arc welding sections of copper alloys thicker than about ½ in., where its high deposition rate is a major advan-

Table 14. Electrode Wires Most Frequently Used in Gas Metal-Arc and Shielded Metal-Arc Welding of Copper and Copper Alloys (a)

Type of electrode	AWS classification	Principal constituents (b)
Copper	ECu (c)	98.0 min Cu+Ag, 1.0 Sn, 0.5 Mn, 0.5 Si, 0.15 P
Silicon bronze	ECuSi	2.8-4.0 Si, 1.5 Sn, 1.5 Mn, 0.5 Fe, rem Cu+Ag
Phosphor bronze	ECuSn-A	4.0-6.0 Sn, 0.10-0.35 P, rem Cu+Ag
Phosphor bronze	ECuSn-C	7.0-9.0 Sn, 0.05-0.35 P, rem Cu+Ag
Aluminum bronze	ECuAl-A1 (c)	6.0-9.0 Al, rem Cu+Ag
Aluminum bronze	ECuAl-A2	1.5 Fe, 9.0-11.0 Al, rem Cu+Ag
Aluminum bronze	ECuAl-B	3.0-4.25 Fe, 11.0-12.0 Al, rem Cu+Ag
Copper nickel	ECuNi	1.00 Mn, 0.6 Fe, 0.50 Si, 29.0 min Ni+Co, 0.6 Ti, rem Cu+Ag

(a) Based on AWS A5.6; see current edition of this specification for complete compositions and qualifications. All electrodes listed are available in both bare and covered forms except ECu and ECuAl-A1, which are not available as covered electrodes for shielded metal-arc welding. (b) Single percentages are maximums unless otherwise stated. Optional elements and impurities have been omitted. For covered electrodes, the compositions are of the metal core. (c) Available only as bare electrodes, for gas metal-arc welding.

tage over gas tungsten-arc welding or shielded metal-arc welding.

The greater rate of heat input to the weld, compared with that for gas tungsten-arc welding, is a disadvantage in some applications because of the wider heat-affected zone.

Nominal conditions for gas metal-arc welding of coppers and copper alloys are shown in Table 13.

Direct current, reverse polarity, is used exclusively for gas metal-arc welding of copper alloys. Argon is normally used for shielding. Helium or mixtures of argon and helium are used where hotter arcs are needed than are possible at given current levels with pure argon.

As shown in Table 13, a square-groove joint is not ordinarily used for welding thicknesses greater than ⅛ in. except for coppers; single-V grooves are used for thicknesses of ⅛ to ½ in. In material thicker than about ½ in., joints are usually prepared with double-V or double-U grooves.

Welding Position. Most gas metal-arc welding of copper alloys is done in the flat position, with spray transfer; fillet welds acceptable for many applications can be produced in the horizontal position. When it is necessary to weld in positions other than flat, gas metal-arc welding is preferred to gas tungsten-arc or shielded metal-arc welding. Gas metal-arc welding in the vertical and overhead positions is usually restricted to the less fluid copper alloys such as aluminum bronzes, silicon bronzes, and copper nickels. Small-diameter electrode wire and low currents are preferred for such applications, and a globular or short-circuiting mode of transfer is ordinarily used.

Electrode Wires (Filler Metals). Compositions of electrode wires used in gas metal-arc welding of copper alloys are shown in Table 14.

Methods. Both semiautomatic and automatic methods were used for gas metal-arc welding of circumferential butt joints in copper nickel tubing in Example 337. In the three other examples in this section, electrode-wire feed, gas flow and current level were automatically controlled.

Gas Metal-Arc Welding of Coppers

The effects of oxygen in causing porosity and reducing the strength of welds in copper, as described for gas tungsten-arc welding of copper, are more pronounced in gas metal-arc welding, because of the greater heat input associated with this process. Gas metal-arc welds of deoxidized coppers compare favorably in density and strength with the welds made using the gas tungsten-arc process. However, the greater heat input and the lesser localization of heat obtained with the gas metal-arc process result in greater porosity and lower strength in the heat-affected zone of welds in coppers that contain insufficient amounts of deoxidizer (especially electrolytic tough pitch copper). Consequently, gas metal-arc welding has less applicability than gas tungsten-arc welding for electrolytic tough pitch copper, oxygen-free copper (alloy 102, OF) or low-phosphorus deoxidized copper (alloy 120, DLP) up to about ½ in. thick.

Nominal conditions for gas metal-arc butt welding of coppers are given in Table 13. In welding joints for which the root opening is up to 1/16 or ⅛ in., argon-helium mixtures are sometimes used instead of pure argon, to obtain higher heat input.

Electrode Wires. The recommended ECu electrode wire contains phosphorus, tin, silicon and manganese as deoxidizers, to minimize porosity. This electrode produces sound, trouble-free welds that are also a good match to copper in color, and have good electrical conductivity. The ECu electrode was used as a basis for the conditions listed in Table 13.

Copper electrode wires of purity higher than ECu are seldom used in gas metal-arc welding of copper, because, as a consequence of the absence of deoxidizers, they usually make welds that are porous. Most of the electrodes listed in Table 14 can be used. Any of the electrodes other than ECu will make dense, strong welds, but the color match will be poor, and the electrical conductivity may be unacceptable.

Joint Design. A square-groove joint is used for single-pass welding of coppers up to ⅛ in. thick, in conjunction with a copper backing bar for zero root opening or a grooved copper backing bar where the root opening is 1/16 in. maximum. A square-groove joint is also used for one-pass-per-side welding of coppers up to about ¼ in. thick.

In welding the single-V-groove joints referred to in Table 13 for thicknesses of ⅜ to about ½ in., the metal is deposited on one side in three or more passes and the root pass is back gouged to sound metal before the last pass is applied to the back of the joint. In some applications, the root pass is applied by gas tungsten-arc welding, and subsequent passes are made by gas metal-arc welding for fast buildup.

Heavy sections (thicker than ½ in.) should be prepared with a double-V or a double-U groove and welded with alternate passes applied to opposite sides of the joint if readily accessible, to minimize distortion. In a small closed vessel, limited access may prevent the use of this technique, and in addition, heat buildup often prevents welding on both sides.

Preheating. Because of the high thermal conductivity of copper, sections thicker than ¼ in. are usually preheated. As shown in Table 13, single-V-groove joints in ¼-in.-thick copper, welded using 1/16-in.-diam electrode wire, are also preheated.

Deoxidized Coppers. Heavy-wall copper pressure vessels (up to about 1½-in. wall), which are usually made from phosphorus-deoxidized copper, in which the residual phosphorus helps obtain maximum weld strength and freedom from porosity, are frequently gas metal-arc welded. To meet the high heat demand in welding these heavy-wall vessels, welding currents and preheat temperatures may be higher than those shown in Table 13.

Similar operating conditions are employed in welding crucibles used for arc melting of refractory metals in controlled atmospheres. The crucibles are typically heavy-wall deoxidized copper cylinders with wall thicknesses up to 1¼ in., diameters of 12 to 48 in., and lengths of 3 to 25 ft. They are made of formed and welded copper plate, because seamless tubes of these sizes are not available. Longitudinal seams are welded, and flanges are welded to each end of the cylinders, by the gas metal-arc process. Such cylinders are heated to 1200 F before welding. Welding is done automatically, to avoid bringing operators into close proximity with heavy metal sections at such high temperature.

Oxygen-Free and Tough Pitch Coppers. The gas metal-arc process is used also in welding oxygen-free (OF) copper in producing crucibles of the type just described for arc melting of refractory metals, although the weld properties are inferior to those produced with deoxidized copper. Because OF copper contains no residual deoxidizer, heating and welding cycles must be kept as short as possible, and gas shielding must be completely effective, to avoid excessive porosity.

Although the strength and soundness of welds in oxygen-bearing coppers such as electrolytic tough pitch (ETP) copper are substantially less than in OF copper, the reduced strength and soundness are seldom important for welds in electrical conductors. Bus bars made of ETP copper are sometimes joined by gas metal-arc welding. The adverse effect of the relatively low electrical conductivity of the filler metal, such as ECu or one of the other standard filler metals listed in Table 14, on the electrical conductivity of the joint can be reduced by providing a large contact area at the joint. For better electrical conductivity, a filler metal with about 0.75% Sn, 0.25% Si and 0.20% Mn is sometimes used for welding of ETP copper bus bars.

Gas Metal-Arc Welding of High-Conductivity Beryllium Copper

Gas metal-arc welding is preferred to gas tungsten-arc welding for joining thicknesses of alloy 175 (high-conductivity beryllium copper) greater than 0.090 in. if the weldment is to be heat treated to obtain maximum weld strength, and for joining thicknesses greater than about ¼ in. if the welding is to be done on precipitation-hardened material. The maximum thickness normally joined by gas metal-arc welding is about ¾ in.

As pointed out in the discussion of gas tungsten-arc welding of alloy 175 (see page 342), important factors in arc welding this alloy are its high thermal and electrical conductivities, oxide-forming characteristics, and response to heat treatment. Although some compromise between weld strength and conductivity may be necessary, high thermal or electrical conductivity is ordinarily the prime objective in welded assemblies of this alloy.

Normal conditions for gas metal-arc butt welding of high-conductivity beryllium copper are given in Table 13. Reverse-polarity direct current is almost always used.

Although argon may be used for shielding gas, greater heat input (usually desirable for welding this alloy) can be obtained with an argon-helium mixture.

Electrode Wires. When high conductivity is desired, as in most welding applications of alloy 175, electrode wire of the same composition as the base metal is used. When lower conductivity is adequate, electrodes made of high-strength beryllium copper (alloys 170 and 172), can be used, and provide easier welding. Because of the precipitation-hardening characteristics of beryllium coppers, the joint strength is always somewhat lower than that of the base metal, depending on the initial condition of the base metal, the welding conditions, and the selection of filler metal.

Other electrode wires, such as ECuSi, ECuAl-A2 or ECuAl-B, also are used in gas metal-arc welding of alloy 175, but these electrode wires (which contain no beryllium) do not develop the high strength obtained with beryllium copper filler metals.

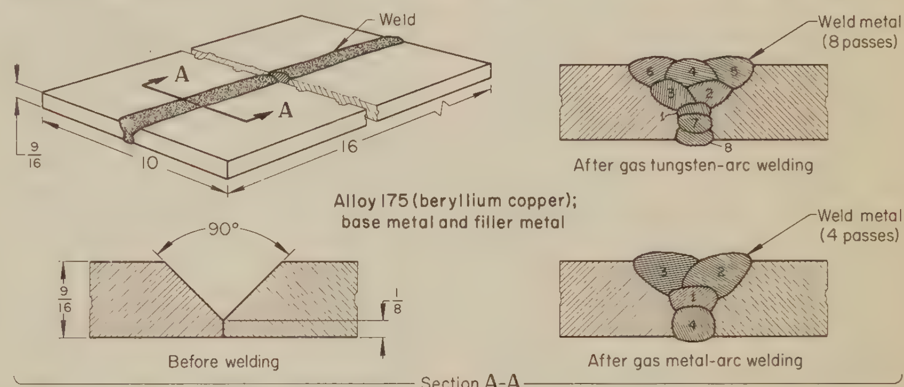
Preheating and Postweld Aging. Sections of alloy 175 thicker than ⅛ in. are usually preheated at 600 to 900 F, depending on section thickness. When beryllium copper filler metal is used, strength can be increased by aging after welding. For alloy 175 the aging treatment is 900 F for 3 hr.

Properties of Weldments. Because of high thermal conductivity and moderate to high strength, alloy 175 is used for welded water-cooled assemblies such as tuyeres for blast furnaces, attrition mills for grinding beryllium chips to powder, and molds for the continuous casting of steel.

Some strength is lost in the weld metal and in the heat-affected zone when alloy 175 is welded. The magnitude of this decrease is affected by the condition and thickness of the base metal, the joint design, welding process and welding conditions. In the following example, the decrease in strength for alloy 175 was less for gas metal-arc than for gas tungsten-arc welding.

Table 15. Decrease in Strength of Alloy 175 After Gas Metal-Arc and Gas Tungsten-Arc Welding (Example 334) (a)

Item	Gas metal-arc welding	Gas tungsten-arc welding
Properties, Using Solution Annealed Work Metal(b)		
Tensile strength, psi:		
Before welding	47,000	48,200
After welding	46,000	37,000
Decrease	2%	23%
Break:		
Before welding	Normal	Normal
After welding	Outside weld	Outside weld
Properties, Using Precipitation-Hardened Work Metal(c)		
Tensile strength, psi:		
Before welding	121,000	98,900
After welding	110,000	81,700
Decrease	9%	17%
Break:		
Before welding	Normal	Normal
After welding	In weld	In weld
Welding Conditions(d)		
Power supply	900-amp motor-generator	500-amp alternator(e)
Electrode	1/16-in.-diam alloy 175	¼-in.-diam EWTh-2
Filler wire	(Consumable electrode)	⅛-in.-diam alloy 175
Shielding gas	Argon, at 30 cfh	Helium, at 25 cfh
Current, amp	325 (dcrp)	240 to 260 (ac, hf-stabilized)
Voltage, v	22	...
Wire-feed rate, ipm	200	...
Travel speed, ipm	11	...
Number of passes	4	8
Preheat temperature, F	1000 to 1200	800 to 900



(a) Data are for welding specimens as illustrated above, in the solution annealed and the precipitation-hardened conditions. Each value for tensile strength is the average of two tests. (b) Solution annealing treatment consisted of heating to 1700 to 1750 F and water quenching. (c) Precipitation hardening was done by reheating the solution annealed specimens for 3 to 4 hr at 900 F and air cooling. (d) For butt joints and single-V-groove welds, as illustrated above; and by use of a manual, water-cooled electrode holder and flat-position welding in both gas metal-arc welding and gas tungsten-arc welding. (e) High-frequency.

Example 334. Comparison of Gas Metal-Arc and Gas Tungsten-Arc Welding for Joining High-Conductivity Beryllium Copper (Table 15)

Comparison studies were made on joining alloy 175 (high-conductivity beryllium copper, 0.6%) by gas metal-arc and gas tungsten-arc welding for several heat-transfer applications. Test specimens were prepared by welding together pieces 5 by 16 by 9/16 in. thick. Joint preparation consisted of beveling the edges to be joined to make a V-groove 7/16 in. deep with a 90° included angle, leaving a root face of ⅛ in., as shown in the drawing in Table 15.

The gas tungsten-arc welds were made by depositing metal in six passes on the face side, back gouging to sound metal, and completing the weld by making two back passes. Before welding, the joint was wire brushed, and each bead was wire brushed to remove any oxide before the next pass.

The work metal was preheated at 800 to 900 F and alternating current was used, both to help keep the surface free of oxide, and to avoid longitudinal bead cracking that might have occurred with direct-current welding.

The gas metal-arc welds were made with three passes on the face side and one back pass, with the root side being ground out to a depth of ⅛ to 3/16 in. before the back pass was made, and with wire brushing of each bead in the same way as for the gas tungsten-arc welds.

Sound welds free from cracking were produced by each process when using the procedure described above and the welding conditions in Table 15, without using a backing gas.

The gas tungsten-arc welding of beryllium copper slightly thicker than ½ in. produced specimens showing a 23% decrease in tensile strength for the solution annealed condition and a 17% decrease in the solution annealed and precipitation-hardened condition, as shown in Table 15. The usual thickness limit is ½ in.

Specimens welded by the gas metal-arc process, working well within its usual limit of ¾-in. thickness for this alloy, showed substantially less decrease in strength. Welded joints made in solution annealed alloys showed only a 2% decrease in tensile strength, while those made in alloys that had been solution annealed and precipitation hardened were 9% lower in strength than the base metal (Table 15). These results may have been affected to a minor extent by the differences in properties of the test specimens used for the two welding processes. As Table 15 shows, in the

precipitation-hardened condition, the specimens used for gas metal-arc welding had a tensile strength of 121,000 psi, while those specimens used for gas tungsten-arc welding had a tensile strength of only 98,900 psi. Considerable variation in the results from precipitation hardening is not unusual. In this instance, determining the percentage of decrease for the two welding processes was the primary objective.

Results of bend tests on specimens welded in the solution annealed condition were acceptable, with no specimen showing more than one crack; the cracks were located near the root edge and were less than ⅛ in. long.

Specimens for all of the tests for qualification of the welding procedure were prepared in the manner described in Section IX of the ASME Boiler and Pressure Vessel Code.

Results by both welding processes were considered acceptable for heat-transfer applications, with gas metal-arc welds being preferred where strength requirements were the most critical; both processes were used in welding a limited number of production assemblies.

Gas Metal-Arc Welding of High-Strength Beryllium Coppers

Alloys 170 (1.7% Be) and 172 (1.9% Be), high-strength beryllium coppers, are more easily welded than high-conductivity beryllium copper, because alloys 170 and 172 have lower melting temperatures, greater fluidity and 50% lower thermal conductivity. As it is for high-conductivity beryllium copper (see preceding section), the gas metal-arc process is generally preferred for welding precipitation-hardened high-strength beryllium coppers in thicknesses of more than ¼ in., and is preferred for thicknesses down to 0.090 in. if heat treatment is to be done after welding.

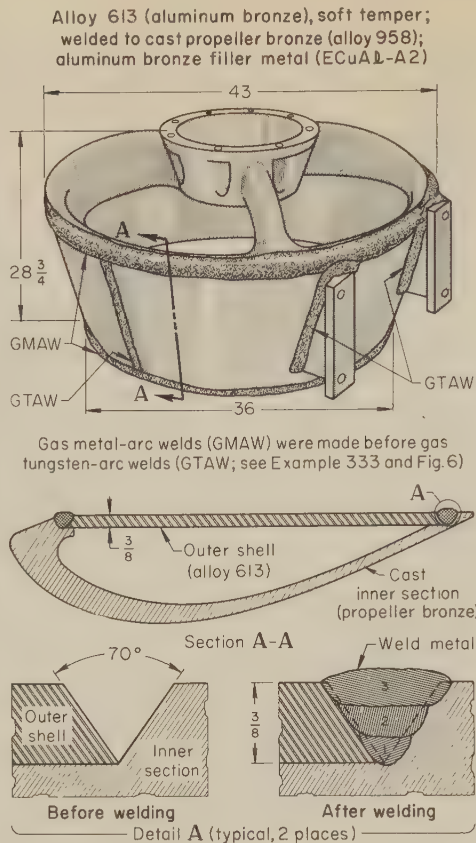
Nominal conditions for gas metal-arc butt welding of high-strength beryllium coppers are given in Table 13.

Mixtures of argon and helium are ordinarily used for shielding gas, in conjunction with reverse-polarity direct current, which helps to prevent oxide buildup during welding. The electrode wire is ordinarily of the same composition as the base metal for joints of maximum strength; electrode wires ECuSi, ECuAl-A2 and ECuAl-B can be used where joint strength is less critical. Preheating, postweld heat treating, and joint design are generally the same as described above for gas tungsten-arc welding of high-strength beryllium coppers.

Gas Metal-Arc Welding of Brasses and Nickel Silvers

Nonleaded brasses, of both the low-zinc type (red brasses) and the high-zinc type (including yellow brasses, tin brasses and special brasses), and nickel silvers can be gas metal-arc welded. Copper-zinc electrodes are not used, because of the violent fuming and loss of zinc that accompanies arc welding with zinc-containing electrodes.

Low-Zinc Brasses. Nominal conditions for butt welding the low-zinc brasses (up to 20% zinc) by the gas metal-arc process are presented in Table 13. Direct current with reverse polarity is always used.



Semiautomatic Gas Metal-Arc Welding

Joint type	Circumferential butt(a)
Weld type	Single-V groove
Welding position	Flat
Number of passes, each weld	Three
Power supply	500-amp rectifier(b)
Electrode wire	3/32-in.-diam ECuAl-A2(c)
Electrode holder	Water cooled
Shielding gas	Argon, at 40 to 45 cfh
Current	425 amp, dcrp
Voltage	35 v
Arc starting	Touch start
Preheat	None

(a) Self-backed joint (see illustration). (b) Constant-voltage type. (c) Spooled.

Fig. 7. Propeller housing, and section showing joints that were gas metal-arc welded (Example 335)

ECuSi electrode wire provides easy welding because it has good fluidity at low current. A 60° single-V-groove joint is used with ECuSi. When ECuSn-C electrode wire is used, principally for better color match, its sluggish flow characteristics make a 70° V-groove advisable for the heavier thicknesses shown in Table 13. The wider groove allows more room for manipulation of the molten weld metal. Except for color, weld-metal properties are comparable when using these two types of electrodes. For welds of redder color and slightly higher conductivity, the low-zinc brasses can also be welded with ECuSn-A electrode wires, but weld strength and hardness are lower.

High-Zinc Copper Alloys. Nonleaded copper alloys with zinc contents ranging from about 20 to 40%, or more (see compositions of high-zinc brasses, tin brasses, special brasses, and nickel silvers in Table 1), can be gas metal-arc welded, although with greater difficulty than the nonleaded low-zinc brasses. Zinc fumes are more severe and the welds have greater porosity and lower strength than in the low-zinc brasses. Both wrought and cast alloys are joined by gas metal-arc welding; massive sections such as manganese bronze ship propellers are regularly repair welded by this process.

Nominal conditions for gas metal-arc butt welding of high-zinc copper alloys (high-zinc or yellow brasses, tin brasses, special brasses, and nickel silvers) are given in Table 13. Operating variables are generally the same when using either ECuAl-A2 (for higher weld strength) or ECuSn-C (for better color match). Preheating is seldom necessary, because these alloys have relatively low heat conductivity. However, preheating helps to limit fuming in some applications, because it permits use of lower current.

Gas Metal-Arc Welding of Phosphor Bronzes

Nominal conditions for gas metal-arc butt welding of phosphor bronzes are given in Table 13. Lead-bearing or other free-machining types are not welded. As with gas tungsten-arc welding (Table 8), the welding conditions are based on the three poorly conductive phosphor bronzes (alloys 510, 521 and 524); higher welding current or slower welding speed is needed for the more conductive alloy 505 (phosphor bronze, 1.25% E).

For thicknesses of ⅜ to ½ in., 90° single-V grooves are used, rather than narrow grooves as for most other poorly conductive copper alloys (Table 13).

Electrode Wires. For joining phosphor bronzes with less than 8% Sn, ECuSn-A electrode wire is generally used. For joining phosphor bronzes with 8 to 10% Sn, ECuSn-C is more often used. Electrode wire that contains about ½% Si is sometimes used to minimize porosity in the weld.

Preheating helps in obtaining complete fusion. Also, it minimizes porosity because the freezing rate of the weld puddle is decreased and more gas is permitted to be evolved before solidification. However, preheating increases the susceptibility of the weld to hot-short cracking and to large columnar grain growth; thus it is common practice to weld with a stringer-bead technique and to peen between layers. A small weld puddle and rapid electrode travel are required.

Interpass temperature should not exceed the preheating temperature (Table 13), because these alloys are hot short.

Gas Metal-Arc Welding of Aluminum Bronzes

Gas metal-arc welding with aluminum bronze electrode wire is the preferred technique for welding aluminum bronze. Because of the comparatively high surface tension of the molten weld metal and the low thermal conductivity of the base metal, welding can be done in all positions. Welds in the vertical and overhead positions are usually made with either the globular or the short-circuiting mode of metal transfer, using electrode wire up to 1/16 in. in diameter.

Nominal conditions for gas metal-arc butt welding of aluminum bronze are given in Table 13. The use of aluminum bronze backing strips or rings in welding metal up to ⅛ in. thick may make it necessary to use helium or argon-helium mixtures as shielding gas, instead of argon as shown in Table 13, for adequate heat input.

Electrode wire ECuAl-A2 is ordinarily used in gas metal-arc welding of aluminum bronze. The 1.5% Fe in this electrode wire makes welds deposited from it less susceptible to hot-short cracking than welds from ECuAl-A1, as is illustrated in Example 336. Welds made with electrode wire ECuAl-B also are free from hot shortness. Joints made with ECuAl-B are also stronger and harder, but less ductile.

Joint Design. The joining of aluminum bronze thicker than about ½ in. requires wider root openings and groove angles than are indicated in Table 13, to avoid bridging and incomplete filling of the joint or to improve penetration because of the increased heat sink in the heavier sections. A short arc, less than ⅛ in. long, is preferred for groove welding of aluminum bronze by the gas metal-arc process.

Combined Processes. Gas metal-arc welding is used in combination with other processes for the fabrication of large and complicated aluminum bronze assemblies. It is often combined with gas tungsten-arc welding, as in the following example.

Example 335. Use of Gas Metal-Arc Welding To Join Outer and Inner Portions of a Propeller Housing (Fig. 7)

Gas metal-arc welding was used to make the circumferential welds on the propeller housing shown in Fig. 7. (The longitudinal seam in the outer shell, and two mounting brackets, were then welded by the gas tungsten-arc process, as described in Example 333.)

The gas metal-arc welds joined the cast inner section and the formed outer shell, as shown in section A-A in Fig. 7. A 35° angle was cast into the edges of the inner-section top and bottom, to mate with a 35° bevel machined on the edges of the formed shell, thus making grooves with 70° included angles for welding (see detail A in Fig. 7).

The shell was tack welded in place, and the two circumferential joints were gas metal-arc welded in three passes each. All welding was done in the flat position using $\frac{3}{32}$-in.-diam ECuAl-A2 electrode wire, reverse-polarity direct current, and argon shielding gas flowing at the rate of 40 to 45 cfh. Other welding conditions are given in the table with Fig. 7.

Preheating. Preheating is seldom necessary in gas metal-arc welding of aluminum bronze (compare Examples 335 and 333). Interpass temperature should not exceed 600 F, because some aluminum bronzes are hot short.

Effect of Base Metal on Weldability. For some applications, changing from one aluminum bronze base metal to another can significantly improve weldability, as in the large condenser shells described in the next example.

Example 336. Effect of Base-Metal Composition on Weldability of Aluminum Bronze (Fig. 8)

In gas metal-arc welding of 20-ton, aluminum bronze condenser shells of the type shown in Fig. 8, three types of joint were involved: butt joints in the shell, T-joints in the baffle section (also of aluminum bronze), and T-joints between external low-carbon steel stiffeners and the copper alloy shell.

Material for the first of three condenser shells was alloy 614, an aluminum bronze containing 2% iron. Neither preheating nor interpass heating was used.

The shell and baffle joints (Fig. 8) were originally joined by gas metal-arc welding with ECuAl-A1 electrode wire and an argon-helium mixture as the shielding gas. The welds cracked severely, because of hot shortness of the weld metal. A change was made to a higher-strength (ECuAl-A2) electrode wire, but then cracking occurred in the heat-affected zone of the base metal, about ⅛ in. from the weld.

The cracking in the heat-affected zone of the aluminum bronze plate was eliminated by changing to alloy 613 base metal, which had the same 7% aluminum content as alloy 614 but with 3.5% iron and 0.2 to 0.5% tin. This adjustment in base-metal composition, together with the change to the ECuAl-A2 electrode, eliminated cracking of welds and base metal, and welding was still done without preheating, to produce assemblies meeting quality standards.

Typical joints of the three types are shown in Fig. 8; welding conditions are given in the accompanying table. Automatic gas metal-arc welding was used on all joints that were easily accessible. Because of difficulties in positioning the heavy assembly in later stages of construction, shielded metal-arc welding was used on some of the less easily accessible stiffener joints.

Welds were inspected visually and with liquid penetrant. Completed condenser-shell assemblies were tested hydrostatically at 3000 psi and were found to be free from leaks. After the first three 20-ton units were completed, three 40-ton condenser-shell assemblies were made using the same welding procedures.

Gas Metal-Arc Welding of Silicon Bronzes

The nonleaded silicon bronzes are readily gas metal-arc welded.

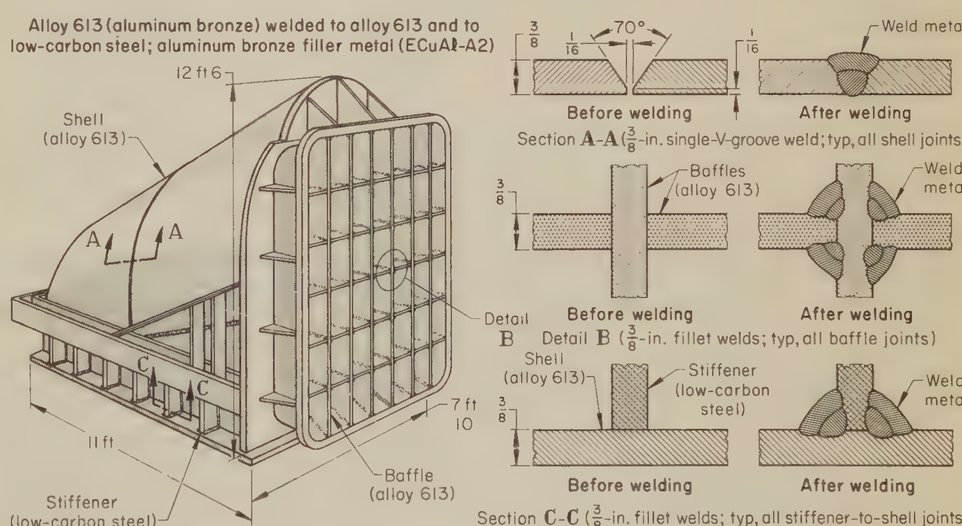
Nominal conditions for gas metal-arc butt welding of silicon bronzes in various thicknesses and joint designs are given in Table 13. To prevent excessive heat buildup in these hot-short alloys, travel speed should be as fast as possible (minimum of 8 in. per minute), and current, as shown in Table 13, is slightly lower than for most other copper alloys. The resulting low heat input to the weld is adequate for complete fusion and good penetration, because of the low thermal conductivity of the silicon bronzes (Table 1).

A thin layer of oxide forms on the weld metal after each pass and must be removed by wire brushing before the next pass.

Electrode Wire. Any silicon bronze alloy can be gas metal-arc welded with ECuSi electrodes. These electrodes are similar in composition to alloy 655 (high-silicon bronze A), the most frequently used silicon bronze, except that they may include up to 1.5% tin instead of, or in addition to, the 1.5% manganese specified as maximum for alloy 655.

Joint Preparation. For thicknesses of ¼ to ¾ in., single, 60° V-grooves are suitable. For silicon bronze alloys thicker than ¾ in., U-grooves or 60° double-V grooves can be used.

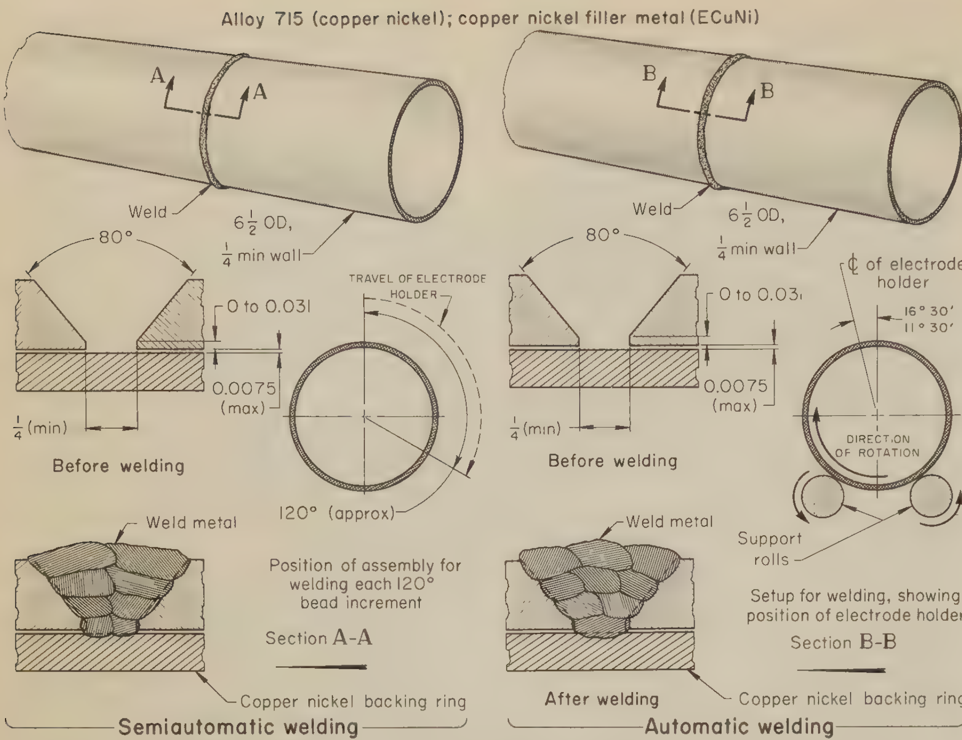
Preheating should not be used, because the silicon bronze alloys are hot



Welding condition	Shell joints (section A-A)	Baffle joints (detail B)	Stiffener-to-shell joints (section C-C)
Welding process	Gas metal-arc	Gas metal-arc	Shielded metal-arc
Joint type	Butt	T	T
Weld type	Single-V groove	Fillet	Fillet
Weld size, in.	⅜	⅜	⅜
Welding position	Flat	Horizontal	Horizontal
Number of passes	Two	Two	Two
Power supply	500-amp rectifier(a)	500-amp rectifier(a)	300-amp rectifier(b)
Electrode	$\frac{1}{16}$-in.-diam ECuAl-A2	$\frac{1}{16}$-in.-diam ECuAl-A2	$\frac{3}{16}$-in.-diam ECuAl-A2 (covered)
Electrode feed, ipm	300	300	Manual
Shielding	70 A – 30 He, at 40 cfh	70 A – 30 He, at 40 cfh	Electrode covering
Current, amp (dcrp)	320	330	200
Voltage (approx), v	30	32	28

(a) Constant-voltage type. (b) Constant-current type.

Fig. 8. Condenser shell, and typical joints that were welded successfully after aluminum bronze components were changed from alloy 614 to alloy 613, and filler metal from ECuAl-A1 to ECuAl-A2, to avoid cracking (Example 336)



Condition	Semiautomatic welding	Automatic welding
Conditions for Gas Metal-Arc Welding		
Joint type	Butt	Butt
Weld type	Single-V-groove	Single-V-groove
Welding position	Horizontal-fixed pipe(a)	Flat (horizontal-rolled pipe)
Power supply (both methods)	Constant-voltage; variable slope, voltage and inductance; and compensation for line-voltage variation	
Electrode	0.035-in.-diam ECuNi	0.062-in.-diam ECuNi
Shielding gas	50% argon, 50% helium	75% argon, 25% helium(b)
Gas-flow rate, cfh	35	200
Current, amp (dcrp)	145 to 185	230 to 250
Voltage, v	21 to 27	28 to 31
Wire speed, ipm	290 to 490	....
Travel speed, ipm	15	18
Preheat	None	None
Interpass temperature	150 F max	150 F max

(a) Each bead was deposited in three 120° increments, with assembly being turned counterclockwise after each increment. (b) Mixed-gas measurements were based on use of a helium flowmeter.

Fig. 9. Setups and weld-buildup sequences for gas metal-arc butt welding of copper nickel tube by semiautomatic and automatic methods (Example 337)

short; interpass temperature must be held below 200 F. Because silicon bronzes have low thermal conductivity, there is no difficulty in obtaining enough heat at the joint for satisfactory welding. Stress relieving of silicon bronze weldments is recommended, to prevent stress-corrosion failure.

Gas Metal-Arc Welding of Copper Nickels

Gas metal-arc welding is the preferred arc welding process for nonleaded copper nickels thicker than about 1/16 in. Welding in the flat position is preferred, but the vertical and overhead positions can be used.

Nominal conditions for gas metal-arc butt welding of nonleaded copper nickels in various joint designs and thicknesses are given in Table 13. Selection of processing conditions is not critical in gas metal-arc welding of these poorly heat-conductive alloys. Alloy 706 is usually welded at slightly higher current or slower speed than alloy 715.

Electrode Wire. Copper nickels are commonly gas metal-arc welded with ECuNi electrode wire, which resembles alloy 715 in that it has a 70-to-30 ratio of copper to nickel. The titanium content (0.15 to 1.00%; see Table 14) of ECuNi serves as a deoxidizer, to minimize porosity and to prevent oxygen embrittlement, and also improves the fluidity of the weld metal.

Joint Design. For gas metal-arc welding of butt joints in nonleaded copper nickels ⅛ in. thick, joint design usually includes a square-groove weld and grooved copper backing, as indicated in Table 13. For thicknesses between ⅛ and ½ in., single-V grooves of 60° to 80° and grooved copper backing are usually employed. (An 80° single-V groove was used in Example 337). For thicknesses greater than about ½ in., double-V or double-U grooves are used.

Backing should be made of copper (or of copper nickel), rather than of carbon, graphite or steel, to avoid reaction with copper and nickel.

Preheating and Postheating. The copper nickel alloys have thermal conductivity equal to or lower than that of low-carbon steel, and no preheating or postheating is needed. Interpass temperature should be kept below 150 F.

Joining of Tubing. Gas metal-arc welding is used extensively for joining copper nickel tubing. The automatic method described in the following example is applicable to tubes larger in outside diameter than 5 in. The offset angles for positioning the electrodes (see Fig. 9) were as follows:

5-in. diam	16 ± 2½° offset
6-in. diam	14 ± 2½° offset
8-in. diam or over	12 ± 2½° offset

A semiautomatic method, usable for pipes 3½ in. in diameter and larger, is compared with the automatic method in the example.

Example 337. Use of Gas Metal-Arc Welding To Butt Weld Copper Nickel Tubing (Fig. 9)

Alloy 715 copper nickel tubing 6½ in. in outside diameter, as shown in Fig. 9, was successfully gas metal-arc butt welded. Wall thickness varied, but was ¼ in. minimum. The joints were prepared by beveling the ends of the tubes to make a V-groove with an 80° included angle and 0.000 to 0.031-in. root face. A backing ring of copper nickel was provided with a minimum outside diameter 0.015 in. smaller than the inside diameter of the tubes. The backing ring was not removed after welding. Before the tubes and backing ring were assembled, the inner surfaces of the tubes, where they were to be in contact with the backing ring, were cleaned to bright metal, as were the beveled ends of the tubes and the outer surfaces for ¼ in. to each side of the joint.

The two tubes and the backing ring were assembled, using a ¼-in. minimum root opening, and tack welded. The tack welds were ground back almost to base metal, and the joint was carefully inspected for starts, stops, crevices and other irregularities that would need to be ground smooth before welding was continued.

Two different methods were used to weld the tube, a semiautomatic method and an automatic method, as detailed in the table with Fig. 9. In the semiautomatic method, the tube assembly was laid flat on a work surface, and each weld bead was applied in three 120° increments from the 12 o'clock position to the 4 o'clock position, with the assembly stationary during each third of a pass. After each 120° increment, the assembly was rolled counterclockwise to present the next 120° segment of the groove to the welder. The weld was completed in eight passes (including two root passes), for each of which the assembly was in three different attitudes on the table, to weld in the horizontal-fixed pipe position from 12 to 4 o'clock (Fig. 9, Section A-A).

In the automatic method, the tube was supported on rolls that turned it continuously while the electrode holder remained fixed for flat-position welding (Section B-B).

Development of the automatic process provided data to ensure that satisfactory results were obtained with only one root pass. By carefully controlling clearance of the backing ring, subsequent passes were made without formation of crevices.

Variations of the technique described in Example 337 were used in similar applications, depending on quantity, lead time, pipe size, service requirements, and availability of equipment. In one such variation, gas tungsten-arc welding was used to fuse a consumable insert in the root of the joint, and the joint was completed by gas metal-arc welding. Another variation was to deposit the root layers by gas metal-arc welding, and to complete the weld manually by the shielded metal-arc process. A similar application on copper nickel pipe, in which the weld was made entirely by shielded metal-arc welding, is described in Example 338.

Table 16. Electrodes and Preheat and Interpass Temperatures Used in Gas Metal-Arc Welding of Coppers and Copper Alloys to Dissimilar Metals (a)

One metal to be welded	Electrodes (and preheat and interpass temperatures) for welding metal in column 1 to: Coppers	Low-zinc brasses	High-zinc brasses, tin brasses, special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels
Copper Alloys							
Low-zinc brasses	ECuSn-C or ECu (1000 F)	....	....	....	....	....	....
High-zinc brasses, tin brasses, special brasses	ECuSi or ECuSn-C or ECu (1000 F)	ECuSn-C (600 F)	....	....	....	....	....
Phosphor bronzes	ECuSn-C or ECu (1000 F)	ECuSn-C (500 F)	ECuSn-C (600 F)	....	....	....	....
Aluminum bronzes	ECuAl-A2 (1000 F)	ECuAl-A2 (600 F)	ECuAl-A2 (600 F)	ECuAl-A2 or ECuSn-C (400 F)	....	....	....
Silicon bronzes	ECuSn-C or ECu (1000 F)	ECuAl-A2 or ECuSi (150 F max)	ECuAl-A2 or ECuSi (150 F max)	ECuSi (150 F max)	ECuAl-A2 (150 F max)	....	....
Copper nickels	ECuAl-A2 or ECuNi or ECu (1000 F)	ECuAl-A2 (150 F max)	ECuAl-A2 (150 F max)	ECuSn-C (150 F max)	ECuAl-A2 (150 F max)	ECuAl-A2 (150 F max)	....
Nickel Alloys							
Nickel and Ni-Cu alloys	ECuNi or ERNiCu-7 (1000 F)	(b)	(b)	(b)	(b)	(b)	ECuNi or ERNiCu-7 (150 F max)
Ni-Cr, Ni-Fe and Ni-Cr-Fe alloys	ERNi-3 (1000 F)	(b)	(b)	(b)	(b)	(b)	ERNi-3 (150 F max)
Steels							
Low-carbon steel	ECuAl-A2 or ECu or ERNi-3 (1000 F)	ECuSn-C (600 F)	ECuAl-A2 (500 F)	ECuSn-C (400 F)	ECuAl-A2 (300 F)	ECuAl-A2 (150 F max)	ECuAl-A2 or ERNi-3 (150 F max)
Medium-carbon steel	ECuAl-A2 or ECu or ERNi-3 (1000 F)	ECuAl-A2 (600 F)	ECuAl-A2 (500 F)	ECuSn-C (400 F)	ECuAl-A2 (400 F)	ECuAl-A2 (150 F max)	ECuAl-A2 or ERNi-3 (150 F max)
High-carbon steel	ECuAl-A2 or ECu or ERNi-3 (1000 F)	ECuAl-A2 (600 F)	ECuAl-A2 (500 F)	ECuSn-C (500 F)	ECuAl-A2 (500 F)	ECuAl-A2 (400 F)	ECuAl-A2 or ERNi-3 (150 F max)
Low-alloy steel	ECuAl-A2 or ECu or ERNi-3 (1000 F)	ECuAl-A2 (600 F)	ECuAl-A2 (600 F)	ECuSn-C (500 F)	ECuAl-A2 (500 F)	ECuAl-A2 (400 F)	ECuAl-A2 or ERNi-3 (150 F max)
Stainless steel	ECuAl-A2 or ECu or ERNi-3 (1000 F)	ECuAl-A2 or ECuSn-C (600 F)	ECuAl-A2 (600 F)	ECuSn-C (400 F)	ECuAl-A2 (150 F max)	ECuAl-A2 (150 F max)	ECuAl-A2 or ERNi-3 (150 F max)
Cast Irons							
Gray and malleable irons	ECuAl-A2 or ECu (1000 F)	ECuAl-A2 or ECuSn-C (600 F)	ECuAl-A2 (600 F)	ECuSn-C (400 F)	ECuAl-A2 (400 F)	ECuAl-A2 or ECuSi (300 F)	ECuAl-A2 or ECuNi (150 F max)
Ductile iron	ECuAl-A2 or ECu (1000 F)	ECuAl-A2 (600 F)	ECuAl-A2 (600 F)	ECuSn-C (400 F)	ECuAl-A2 (150 F max)	ECuAl-A2 or ECuSi (150 F max)	ECuAl-A2 or ECuNi (150 F max)

(a) Electrode selections in table are based on weldability, except where mechanical properties are usually more important. Preheating is usually used only when at least one member is thicker than ⅛ in. or is highly conductive; see text. Preheat and interpass temperatures are subject to adjustment based on size and shape of weldment. (b) These combinations are seldom welded; as a starting point in developing welding procedures, use of ECuAl-A2 electrodes is recommended, except for combinations including phosphor bronzes.

Gas Metal-Arc Welding of Unlike Copper Alloys

Gas metal-arc welding can be used for joining nearly all combinations of the weldable copper alloys, with the major factor in developing the welding procedures being the selection of suitable electrode-wire compositions and preheat temperatures. As in other welding of dissimilar metals, the arc is usually directed at the more conductive metal of the combination.

Electrodes and preheat and interpass temperatures for gas metal-arc welding of various combinations of unlike copper alloys are given in Table 16. This table includes all of the alloys listed for gas tungsten-arc welding in Table 12, plus the high-zinc brasses, tin brasses and special brasses.

As shown in Table 16, ECuAl-A2 comes close to being a universal electrode for gas metal-arc welding of unlike copper alloys, although it is incompatible with phosphor bronzes. Silicon bronze (ECuSi) and phosphor bronze (ECuSn-C) electrodes are useful for many combinations of copper alloys that do not contain nickel. Copper electrodes (ECu) are suitable for the final welding passes for welding copper to any of the commonly welded copper alloys, using alloy electrodes to produce the preliminary weld deposits. Copper nickel electrodes (ECuNi) are generally used to join copper to copper nickel.

Usually, a suitable electrode for welding unlike copper alloys is one that is used for welding one of the metals of the combination to itself. A notable exception to this general rule is in the welding of silicon bronzes to copper nickel. The only electrode that can be used successfully for joining this combination is ECuAl-A2.

Preheating. As with gas tungsten-arc welding, preheating is not needed in joining metal less than about ⅛ in. thick, unless at least one member has high thermal conductivity. In joining greater thicknesses, the need for preheating and the choice of preheat temperature are influenced by the joint design and welding conditions.

When joining copper to other copper alloys, the need to provide enough heat to melt the highly conductive copper overrides other considerations,

and the preheat temperature for copper must be used. For instance, when thick copper is welded to copper nickel, required preheat temperature is 1000 F, although copper nickel ordinarily is held below 150 F between passes. The need for enough heat to melt the copper overrides the concern with hot shortness of the copper nickel. The welded assembly is handled carefully until it has cooled below 150 F. Table 16 also shows that the heat sensitivity of copper nickel overrides other considerations when it is welded to other copper alloys and to other metals.

Gas Metal-Arc Welding of Copper Alloys to Dissimilar Metals

The main consideration in gas metal-arc welding of copper or a copper alloy to a ferrous or nickel alloy is dilution. It is not difficult to make welds as strong as the weaker of the base metals, but it may be difficult to retain the ductility demanded by service requirements. The most serious effect of excessive dilution is unsoundness in the form of shrinkage cracks, which can start in the weld metal and propagate into the base metal.

Either of two methods is frequently used to control dilution when gas metal-arc welding combinations involving copper alloys: (*a*) braze weld one side of the joint, thus promoting a minimum amount of dilution on that side, and weld the other side; and (*b*) overlay one or both joint surfaces with a buffer metal.

Braze Welding Method. Braze welds can be used to join copper, aluminum bronzes or copper-zinc alloys to low-carbon or alloy steel, stainless steel, cast iron or nickel alloys. Other copper alloys are more difficult to join to ferrous and nickel alloys by this method. Silicon bronzes make brittle welds; phosphor bronzes and copper nickels make porous welds, especially with ferrous alloys, when welded in this way.

Overlay Method. The other method of controlling dilution is the application of an overlay, on one or both sides of the joint. The overlay metal can be the same as the electrode (filler metal) chosen to weld the joint, or it can be another type chosen principally for its ability to act as a buffer between two incompatible base metals to minimize or eliminate their mixing.

With one or both joint surfaces overlaid, the electrode for welding the remainder of the joint can be chosen with much more freedom, on the basis of its compatibility with the overlay metal and the opposite base metal, or with the two overlay metals, rather than its compatibility with the two original base metals.

When coppers or copper nickels are welded to nickel alloys by the overlay method, the copper side usually is coated with a filler metal that has a substantial content of nickel (see Table 16), to produce a high-nickel surface to weld to the copper or copper nickel.

When silicon bronzes are joined to ferrous or nickel alloys, the silicon bronze side of the joint is ordinarily overlaid with ECuAl-A2. This filler metal is generally suitable for overlaying copper alloys that are being gas metal-arc welded to a ferrous or nickel alloy (see Table 16).

Welding Copper Alloys to Ferrous Metals. Besides the possibility of dilution of filler metal by copper in welding copper alloys to ferrous metals, there is the possibility of iron pickup from the ferrous side.

Aluminum bronzes can tolerate considerable dilution of this type, and copper nickels can tolerate a somewhat lesser amount. In welding these alloys to ferrous metals, care must be taken to be sure the iron is well penetrated, in order that the joint will be stronger than a braze welded joint, which might separate at the iron interface under heavy stress. Overlaying is not usually necessary in welding copper nickels or aluminum bronzes to steel. Nominal conditions for welding these two combinations are given in Table 13.

In the application described in Example 336 (Fig. 8), low-carbon steel stiffeners were gas metal-arc welded to a shell of alloy 613 without any precautions beyond those used on bronze-to-bronze welds; the filler metal was ECuAl-A2.

Commercial coppers can be joined to ferrous metals, in most cases also without the use of an overlay, when the nickel filler metal ERNi-3 is used. Table 13 shows nominal conditions for gas metal-arc welding commercial coppers to steel.

The electrode (filler metal) most often used for gas metal-arc welding copper and copper alloys to ferrous metals is ECuAl-A2 (see Table 16). Both overlaying and weld buildup can be done with the same electrode, or a different electrode can be used for buildup. A common practice is to use ECuAl-A2 for overlaying and to complete the weld with any desired electrode that is shown as compatible in Table 16. This technique cannot be used where one member of the combination to be joined is a phosphor bronze.

Table 13 gives conditions for using ECuAl-A2 for gas metal-arc welding silicon bronze to steel. Excessive dilution of the silicon bronze should be avoided, by the use of an overlay. In all welds between copper alloys and ferrous alloys, it is important for maximum weld strength that enough penetration be achieved on the ferrous side of the joint to effect a weld interface rich with an iron alloy.

Welding to Nickel Alloys. The welding of copper alloys to nickel alloys by the overlay method is generally straightforward, as a result of the mutual solubility of copper and nickel in all proportions. As shown in Table 16, electrodes used in gas metal-arc welding nickel alloys to coppers and copper nickels are ERNi-3 (nickel), ERNiCu-7 (nickel copper), and ECuNi (copper nickel). The copper alloy joint surface should be overlaid with a weld deposit at least ⅛ in. thick before the remainder of the joint is welded.

Aluminum bronze electrodes (ECuAl-A2) are generally suitable for welding alloy combinations in this category. They are the only electrodes that can be used to weld silicon bronzes to nickel alloys such as Monel without cracking. Even with aluminum bronze electrodes, it is advisable to overlay the nickel with filler metal before completing the weld, to minimize the interaction of silicon and nickel that might result in crack-prone weld metal.

Shielded Metal-Arc Welding

Compared with shielded metal-arc welding as applied to low-carbon steel, the process as applied to copper and copper alloys uses larger root openings, wider groove angles, more tack welds, higher preheat and interpass temperatures, and higher currents. For list of covered electrodes, see Table 14.

Shielded metal-arc welding of copper and copper alloys is almost always restricted to flat-position welding; out-of-position welding by this process is usually limited to the joining of phosphor bronzes and copper nickels.

Shielded metal-arc welding is not recommended for most alloys (Table 1) because of the reduced mechanical properties and the possibility of unsoundness that can be expected.

Coppers. Problems of porosity and low weld strength due to oxygen content of the base metal and oxygen absorption during welding, are more severe in joining coppers by this process than by gas-shielded processes. Shielded metal-arc welding is not advised for joining commercial coppers (Table 1).

Brasses and Nickel Silvers. The low-zinc brasses, high-zinc brasses, tin brasses, special brasses and nickel silvers listed in Table 1 are not generally recommended for welding by the shielded metal-arc process. However, some brasses are occasionally welded by this process when requirements are not rigorous.

Phosphor bronze electrodes such as ECuSn-A and ECuSn-C have been used for welding the low-zinc brasses. The base metal is preheated and held at 400 to 500 F. Weld metal is applied in narrow and shallow stringer beads.

The high-zinc copper alloys can be welded with ECuAl-A2 (aluminum bronze) electrodes. Preheat and interpass temperatures are 500 to 700 F. The arc is held directly on the molten weld puddle rather than toward the base metal, and advanced slowly in order to minimize zinc volatilization.

Phosphor Bronzes. Shielded metal-arc welding is done to a limited extent on the phosphor bronzes listed in Table 1. Covered electrodes ECuSn-A and ECuSn-C are used interchangeably.

The phosphor bronzes flow sluggishly and must be preheated to 300 to 400 F, especially for thick sections. However, because of the hot shortness of these alloys, the interpass temperature must not be permitted to go above the preheat temperature. This is achieved by welding rapidly with light passes. In groove welding, the first two passes are made with a weaving technique. Width of the weave should not exceed two electrode diameters. The remaining passes are made without appreciable transverse weaving and with the use of narrow stringer beads. The development of a coarse dendritic structure of low strength and ductility is minimized by control of preheat and interpass temperature and the use of this method

of deposition. Hot peening after welding helps to break up coarse grain structure. For maximum ductility, the welded assembly should be postheated to 900 F and cooled rapidly.

Joint grooves should be wide (80° to 90°), to achieve proper "washing" of the groove walls.

Aluminum Bronzes. Shielded metal-arc welding is done readily on aluminum bronzes in both the wrought and cast forms. The aluminum oxides that form on the surface of these alloys are removed by the fluxing action of the electrode coatings.

Except for thin sections, a 70°-to-90° V-groove joint is used, usually with a backing strip of the same composition as the base metal. Deposition technique and bead thickness are not critical, because the weld metal has excellent hot strength and ductility.

Aluminum bronze ECuAl-A2 and ECuAl-B electrodes are used for welding the aluminum bronze alloys 613 and 614, which contain about 7% Al. Thick sections of these alloys may need preheating, usually to 400 F, and control of interpass temperature at 400 F. Depending on section thickness and over-all mass, however, preheat and interpass temperature may vary between about 150 and 800 F. Weldments of the 7% aluminum bronzes need not be heat treated after welding.

Aluminum bronzes having an aluminum content higher than 7% are usually welded with electrodes that contain more aluminum than do ECuAl-A2 and ECuAl-B. The higher-aluminum bronze electrodes are ECuAl-C, ECuAl-D and ECuAl-E, which are best known as surfacing electrodes (see AWS A5.13), and which have nominal aluminum contents of 12.5, 13.5 and 14.5%, respectively, and correspondingly increasing strength. In welding high-aluminum bronzes, thick sections may require preheating up to 1150 F, and fan cooling may be necessary to avoid cracking. Also, these alloys may require annealing at 1150 F, followed by fan cooling, for stress relief.

Silicon Bronzes. Shielded metal-arc welding of silicon bronzes is usually done with ECuAl-A2 aluminum bronze electrodes. Welding temperature is easily attained, since silicon bronzes have low thermal conductivity. However, because the alloys are hot short, the metal should not be preheated and interpass temperature should not exceed 200 F.

Groove dimensions are similar to those used for welding similar steel joints. Metal thicknesses up to 5/32 in. can be welded with square grooves; thicker sections, with a single-V or double-V groove of 60° included angle.

Properties of welds made in silicon bronzes by shielded metal-arc welding are usually substantially lower than those of welds made by the gas-shielded processes, and may not meet code or design requirements for strength. Peening will reduce residual stress and minimize distortion.

Copper Nickels. Shielded metal-arc welding is done on copper nickels in both the wrought and cast forms. Having thermal conductivity close to that of low-carbon steel, these alloys behave like steel in most respects and are as readily welded as steel by the shielded metal-arc process. The 70-30 copper nickel ECuNi electrodes (Table 14) are used in welding the copper nickel alloys 706 and 715, usually with reverse-polarity direct current.

The weld deposits ordinarily have a high center crown, and the slag is viscous when molten and adherent when cold. Therefore, special care is needed to ensure complete slag removal before complete solidification of the weld, to prevent slag entrapment when cleaning between passes.

These alloys can be shielded metal-arc welded in all positions with good results, although best results are obtained in flat-position welding. This process is preferred in some applications where access to the joint is limited, as in the butt welding of copper nickel pipe described in the example that follows.

Example 338. Shielded Metal-Arc Butt Welding of Copper Nickel Pipe

In an application similar to the gas metal-arc welding described in Example 337, various sizes of pipe made of alloy 715 (copper nickel, 30%) were butt welded by the shielded metal-arc process, because of limited access to the joint. The pipe ranged in outside diameter from 2½ to more than 6 in.

The butt joints most commonly welded were accessible from the outside only, and therefore had V-grooves and backing. For wall thicknesses of ¾ in. and less, a single-V joint was used with an 80° included angle, 1/16-in. root face, and minimum root openings of 3/16 in. for pipe of 3-in. OD or less, and ¼ in. minimum for larger diameters. For thicknesses over ¾ in., a single-U joint was used with the same root face and root openings. For either single-V or single-U joints, a maximum clearance of 0.015 in. was maintained between the backing ring and the inside diameter of the pipe. Tight fit of the backing in all joints was important, to prevent slag from entering between the base metal and backing.

Weld were made in all positions, using ECuNi electrodes with direct current, reverse polarity. Typical electrode diameters and welding currents were:

3/32-in.-diam electrode	50-100 amp
1/8-in. diam	70-130
5/32-in. diam	90-160

No preheat was used, and interpass temperature did not exceed 150 F. A stringer-bead technique was used for the root passes and, where necessary, for other passes. At no time did average bead width exceed four electrode diameters. All starts, stops and crevices were ground or burred to remove porosity or to prevent slag entrapment. Starts and stops were staggered both within and between weld layers.

Liquid-penerant and visual inspection were done on completion of each layer (root, intermediate, and finish). The completed welds were inspected radiographically.

Shielded metal-arc welding was also used for butt welding of pipe joints without a backing ring where the inside of the pipe was accessible for welding. Under such conditions, one or more passes were deposited in the root from the back side (inside) of the weld. The opposite side (outside) of the root was ground to sound metal before subsequent passes were deposited on the outside of the joint. From the standpoint of welder accessibility in this type of double-welded joint, the maximum distance, *L*, of any part of the weld groove from the open end of the pipe varied with the outside diameter of the pipe as follows:

OD, in.	*L* (max), in.	OD, in.	*L* (max), in.
2½	4	4	7
3	5	5	8
3½	6	6 up	10

Safety

During welding of copper alloys, the use of an effective ventilation system that protects operators and recovers dusts, fumes and mists is more critical than in welding most other metals, because most copper alloys contain at least small amounts of volatile toxic alloying elements.

Zinc fumes will produce an illness known as "zinc chills", but the effect is not cumulative. Small amounts of arsenic, antimony, lead or tellurium also may be hazardous.

Welding of beryllium-containing alloys is of special concern. Airborne particles of beryllium compounds are a health hazard if inhaled. Operations such as welding or grinding, which create a fine, inhalable dust or fume, should not be permitted to raise the beryllium concentration in the air above minimum-recommended limits. A system providing the required ventilation may be needed to avoid unsafe occupational exposures.

The ANSI standard Z49.1, "Safety in Welding and Cutting", should be followed strictly when welding copper and copper alloys. Recommendations on respiratory protection and on ventilation during welding are given in the AWS "Welding Handbook", 6th Ed., Section 1, p 9.24-9.31. Another source of useful information on safety is "Beryllium and Its Compounds" (revised 1964), Hygiene Guide Series, American Industrial Hygiene Assn.

Other Examples on Welding of Copper Alloys

Examples of arc welding of copper in other articles in this volume are listed in Table 17. In addition to examples of processes described in this article are examples of plasma-arc welding, electron beam welding, and percussion welding. The second half of the table refers to examples of welding copper or copper alloys to other metals.

Resistance welding of copper and copper alloys is dealt with in the article that begins on page 475; brazing, in the article beginning on page 685.

Table 17. Examples of Welding of Copper and Copper Alloys in Other Articles in This Volume

Welding of Copper

Example 144. Change from gas tungsten-arc to plasma-arc welding of BCuP-5-clad copper terminals on a computer memory grid

Example 478. Comparison of gas tungsten-arc welding, furnace brazing, and electron beam welding of restrained joints in alloy 175

Example 482. Multiple-tier electron beam welding of BCuP-5-clad copper terminals

Welding of Copper to Other Metals

Example 135. Change from shielded metal-arc to gas tungsten-arc welding of naval brass to low-carbon steel

Example 175. Percussion welding of tinned copper leads to copper alloy terminals

Example 177. Percussion butt welding of a 60Pt-40Rh wire to tinned copper wires

Example 180. Change from silver brazing to percussion welding of a silver – cadmium oxide contact to a copper backing strip

Example 497. Electron beam welding of a flanged copper (alloy 102) nozzle to a type 304 stainless steel tube

Arc Welding of Magnesium Alloys

*By the ASM Committee on Fabrication of Magnesium**

MOST MAGNESIUM ALLOYS can be welded by the gas tungsten-arc and gas metal-arc processes. These welding processes are described in the articles that begin on pages 113 and 78.

Weldability. All magnesium alloys in Table 1 are weldable, but they are not equivalent to each other in weldability. Table 1 rates their weldability on a scale of A (excellent) to D (limited). The rating is based largely on freedom from susceptibility to cracking, and to some extent on joint efficiency. Under the most favorable welding conditions, including favorable joint design, it is possible to obtain joint efficiencies of 60 to 100% for virtually all of the magnesium alloys. Alloys rated A in Table 1 are likely to have correspondingly high joint-efficiency ratings.

In the magnesium-aluminum-zinc alloys (AZ31B, AZ61A, AZ63A, AZ80A, AZ81A, AZ91C and AZ92A), aluminum content up to about 10% aids weldability by helping to refine the grain structure, while zinc content of more than 1% increases hot shortness, which may cause weld cracking. The alloys that have high zinc content (ZH62A and ZK51A) are highly susceptible to cracking, and have poorer weldability.

The thorium-containing alloys HK31A, HM21A and HM31A have excellent arc weldability and are rated B+ or A in Table 1.

Welds in magnesium alloys are characterized by a fine grain size, averaging less than 0.01 in. Magnesium alloys containing more than 1.5% aluminum are susceptible to stress corrosion, and residual stresses must be relieved.

Filler Metals

Compositions of the four most commonly used electrode wires for gas metal-arc welding, and filler metals (when used) for gas tungsten-arc welding, are given in Table 2. The choice of electrode wire or filler metal is governed by the composition of the base metal.

Electrode wires or filler metals having compositions conforming to ER AZ61A or ER AZ92A are considered satisfactory for welding wrought alloys AZ10A, AZ31B, AZ31C, AZ61A, AZ80A, ZE10A and ZK21A (to themselves or to each other). ER AZ61A is usually preferred because it is the less costly. The same electrode wires or filler metals are used for joining any one of the above alloys to elevated-temperature alloys HK31A, HM21A, and HM31A. However, when the elevated-temperature alloys are joined to each other, ER EZ33A is recommended.

The choice of electrode wire or filler metal for welding wrought alloys to cast alloys should follow the recommendations outlined above, except that ER AZ101A may be used instead of ER AZ61A or ER AZ92A.

When cast alloys are joined to cast alloys, ER AZ101A electrode wire or filler metal is usually recommended. However, for joining HK31A and HZ32A (to themselves or to each other), ER EZ33A is preferred; for joining HK31A and HZ32A to any of the other cast alloys, ER AZ101A is used.

Shielding Gases

Only the inert gases are used for shielding in arc welding of magnesium alloys. Argon is the most widely used. Helium and various mixtures of argon and helium have also proved satisfactory, but because of the higher cost per unit volume of helium, and because two to three times more helium than argon is required for the same degree of shielding, the use of pure helium has gradually decreased. In 11 of the 13 examples in this article, argon was the shielding gas (see Table 12).

Joint Design

Typical joint designs for gas-shielded arc welding of various thicknesses of magnesium alloy sheet and plate are presented in Table 3. As shown there, the metal-thickness ranges vary for gas tungsten-arc welding in accordance with the type of current used (alternating, straight-polarity direct, and reverse-polarity direct), and vary for gas metal-arc welding in accordance with the mode of metal transfer.

Table 1. Relative Arc Weldability of Magnesium Alloys
(A = excellent; B = good; C = fair; D = limited weldability)

Alloy	Rating	Alloy	Rating
Casting Alloys		ZH62A	C−
AM100A	B+	ZK51A	D
AZ63A	C	ZK61A	D
AZ81A	B+	**Wrought Alloys**	
AZ91C	B+		
AZ92A	B	AZ10A	A
EK30A	B	AZ31B,C	A
EK41A	B	AZ61A	B
EZ33A	A	AZ80A	B
HK31A	B+	HK31A	A
HZ32A	C	HM21A	A
K1A	A	HM31A	A
QE22A	B	ZE10A	A
ZE41A	C	ZK21A	B

Edges are prepared by milling, sawing, shearing, arc cutting, chipping, planing, routing, sanding or filing.

Sheet up to about 0.080 in. thick is generally single sheared; double shearing is preferred for sheet thicker than 0.080 in.

Double-bevel edges are preferred over single-bevel edges because less distortion occurs in welding.

Fit-up. Components of weldments should fit closely at abutting edges, preferably with no root opening, although a root opening up to 1/16 in. is usually permissible. If tack welds are used, the first tack should be a short distance from the end of a seam.

Best practice in tack welding is to use 1/8-in. tacks spaced 1 to 2 in. on centers for sheet up to 0.065 in. thick, and 1/4-in. tacks spaced 4 to 5 in. on centers for sheet or plate from 0.065 through 1/4 in. thick.

Welding fixtures must be rigid enough to resist movement of the workpieces during welding. Hold-down bars must exert enough pressure to keep the edges from overlapping or rising away from the backing bar or plate. Backing plates are made of steel, magnesium, aluminum or copper, and are cut with a small groove that is positioned directly under the seam. They prevent excessive metal drop-through and minimize distortion. Depth of the grooves in backing plates depends on base-metal thickness, on the welding process used, and on whether or not the joint has a root opening. Typical groove depths are given in Table 4.

Surface Preparation

Magnesium alloys are usually supplied with either an oil coating, an acid pickled surface, or a chromate coated surface. Surfaces and edges must be cleaned just before welding to remove oxides and dirt picked up during forming, assembly and fixturing. It is also important that the electrode wire or filler metal be mechanically or chemically cleaned. A partly used spool of electrode wire or filler metal should

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Several of the examples presented in this article were contributed by members of other Metals Handbook welding committees.

be stored in a manner that will protect it from dirt between welding jobs.

Mechanical cleaning with aluminum or stainless steel wool, aluminum oxide abrasive cloth, or power wire brushes (stainless steel bristles) is preferred for most production jobs. In shops where chemical finishing equipment is available, a cleaning bath of 24 oz chromic acid, 5⅓ oz ferric nitrate, 1/16 oz potassium fluoride, and water to make 1 gal can be used. Parts are dipped in this bath, which is maintained at 70 to 90 F, for about 3 min, then are rinsed thoroughly in hot water and dried in air. The tank should be made of ceramic or stainless steel, or lined with lead, synthetic rubber, or a vinyl-base material.

Preheating

The need for preheating is determined largely by section thickness and amount of restraint. Thick sections, particularly if the magnitude of joint restraint is small, seldom need preheating. Thin sections and highly restrained joints often require preheating to prevent weld cracking, particularly in the high-zinc alloys.

Maximum preheat temperatures for all of the common cast magnesium alloys are given in Table 5. In practice, if preheating is used, the temperature is usually less than the maximum shown in Table 5. (As Table 12 shows, preheating was used in only four of the 13 examples in this article, and the preheat temperatures were substantially lower than the maximum temperatures given in Table 5.)

Gas Metal-Arc Welding

Power supplies used for welding magnesium alloys furnish reverse-polarity direct current. Constant-voltage machines must be used for short-circuiting welding and are generally preferred for spray-arc welding. Constant-current (drooping volt-ampere output) machines can be used for spray-arc welding and are sometimes advantageous for welding that is performed at a current level near the minimum for spray-arc transfer, because weld spatter is less. Special constant-voltage machines designed to pulse the current output must be used in pulsed-arc welding. For detailed information on power supplies and modes of metal transfer, see the article on Gas Metal-Arc Welding, page 78.

Electrode holders, wire feeders, and related equipment used for gas metal-arc welding of magnesium alloys are generally the same as those used for welding other metals. Detailed discussions and illustrations will be found in the above-cited article.

Modes of Metal Transfer. Three modes of metal transfer are suitable for welding magnesium alloys: short-circuiting, pulsed-arc, and spray transfer. Pulsed-arc transfer can be achieved only with a power supply designed to produce a pulsing secondary current. Without the pulsing feature, the type of transfer that would be obtained in the specific operating range of current, wire feed, and wire size for this process would result in globular transfer, which is not suitable for welding magnesium alloys.

Each of the three modes of transfer is best suited to a specific (sometimes overlapping) range of base-metal thickness and welding current, as shown in Table 6. Curves that show the relations among current, electrode-wire size, and wire-feed rate for each mode are presented in Fig. 1.

It is important to select the mode of transfer that is best suited to the metal thickness. In the example that follows, welding was first done with

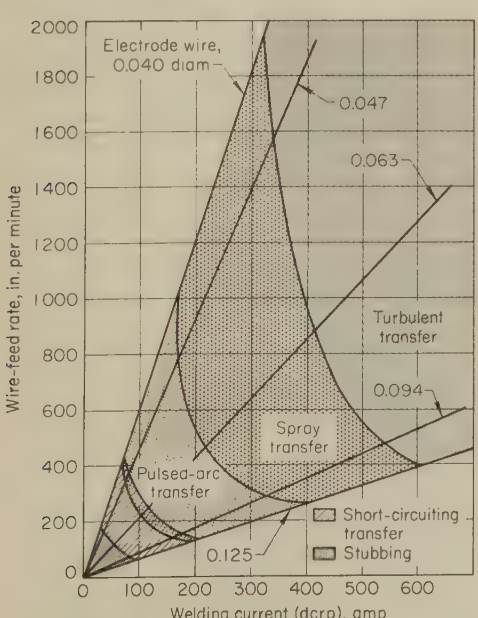


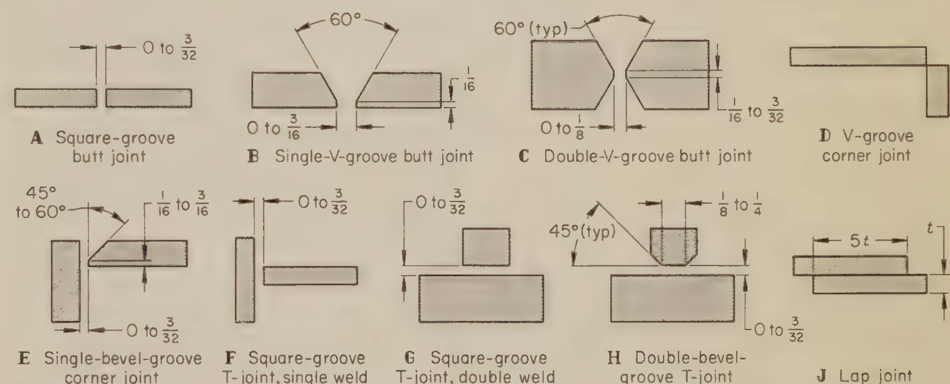
Fig. 1. Effect of wire-feed rate and welding current on mode of metal transfer for various sizes of electrode wire in argon-shielded gas metal-arc welding of magnesium alloys

Table 2. Compositions of Electrodes and Filler Metals Used in Gas-Shielded Arc Welding of Magnesium Alloys (AWS A5.19-69)

Element	ER AZ61A	ER AZ101A	ER AZ92A	ER EZ33A
Aluminum	5.8 to 7.2	9.5 to 10.5	8.3 to 9.7	...
Beryllium	0.0002 to 0.0008	0.0002 to 0.0008	0.0002 to 0.0008	...
Manganese	0.15 min	0.13 min	0.15 min	...
Zinc	0.40 to 1.5	0.75 to 1.25	1.7 to 2.3	2.0 to 3.1
Zirconium	...	...	...	0.45 to 1.0
Rare earth	...	...	...	2.5 to 4.0
Copper	0.05 max	0.05 max	0.05 max	...
Iron	0.005 max	0.005 max	0.005 max	...
Nickel	0.005 max	0.005 max	0.005 max	...
Silicon	0.05 max	0.05 max	0.05 max	...
Others (total)	0.30 max	0.30 max	0.30 max	0.30 max
Magnesium	Remainder	Remainder	Remainder	Remainder

Table 3. Typical Joint Designs Used for Gas-Shielded Arc Welding of Various Thicknesses of Magnesium Alloy Sheet and Plate

Weld and joint type (see illustration)	Applicable range of work-metal thickness, in.(a)					
	Gas tungsten-arc welding(b)			Gas metal-arc welding(c)		
	Ac	Dcsp	Dcrp	Short-circuiting arc	Pulsed arc	Spray arc
A(d)	0.025 to ¼	0.025 to ½	0.025 to 3/16	0.025 to 3/16	0.090 to ¼	3/16 to ⅜
B(e)	¼ to ⅜	¼ to ⅜	3/16 to ⅜	(f)	3/16 to ¼	¼ to ½
C(g)	⅜(h)	⅜(h)	⅜(h)	(f)	(f)	½(h)
D(j)	0.040 to ¼	0.040 to ¼	0.040 to ¼	1/16 to 3/16	1/16 to ¼	3/16 to ½
E(k)	3/16(h)	3/16(h)	3/16(h)	(f)	⅛ to ¼	¼(h)
F(m)	0.025 to ¼	0.025 to ½	0.025 to 5/32	1/16 to 5/32	0.090 to 3/16	5/32 to ⅜
G(n)	1/16 to 3/16	1/16 to ⅜	1/16 to ⅛	1/16 to 5/32	0.090 to ¼	5/32 to ¾
H(p)	3/16(h)	⅜(h)	⅛(h)	(f)	¼ to ⅜	⅜(h)
J(q)	0.040(h)	0.040(h)	0.025(h)	0.040 to 5/32	0.090 to ¼	5/32(h)



A Square-groove butt joint; B Single-V-groove butt joint; C Double-V-groove butt joint; D V-groove corner joint; E Single-bevel-groove corner joint; F Square-groove T-joint, single weld; G Square-groove T-joint, double weld; H Double-bevel-groove T-joint; J Lap joint

(a) Suggested minimum and maximum thickness limits. (b) Using 300-amp ac or dcsp, or 125-amp dcrp. (c) Using 400-amp dcrp. (d) Single-pass complete-penetration weld. Suitable for thin material. (e) Complete-penetration weld. Suitable for thick material. On material thicker than suggested maximum, use double-V-groove butt joint to minimize distortion. (f) Not recommended because spray-arc welding is more practical or economical, or both. (g) Complete-penetration weld. Used on thick material. Minimizes distortion by equalizing shrinkage stress on both sides of joint. (h) No maximum. Thickest material in commercial use could be welded in this type of joint. (j) Single-pass complete-penetration weld. For material thicker than suggested maximum, use single-bevel-groove corner joint because it requires less welding, especially if a square corner is required. (k) Single-pass or multiple-pass complete-penetration weld. Used on thick material to minimize welding. Produces square joint corners. (m) Single-weld T-joint. Thickness limits are based on 40% joint penetration.

(n) Double-weld T-joint. Suggested thickness limits based on 100% joint penetration. (p) Double-weld T-joint. Used on thick material requiring 100% joint penetration. (q) Single or double-weld joint. Strength dependent on size of fillet. Maximum strength in tension on double-weld joints is obtained when lap equals five times the thickness of the thinner member.

globular transfer, but was changed to spray transfer, with improved quality and an accompanying decrease in cost. In this application, pulsed-arc transfer could probably have been used successfully if the appropriate type of power supply had been available.

Example 339. Short-Circuiting vs Globular Transfer in Gas Metal-Arc Welding of Sheet (Table 7)

A fabricator had been using automatic gas metal-arc welding with the globular mode of transfer (not generally recommended) for production welding of 58-in.-long butt joints in 0.110-in.-thick ZE10A-H24 sheet. The tightly fitted square-groove joints were single-pass seam welded in a mechanized setup that included hold-downs and a backing bar. Welding was done at the maximum practical speed that could be attained within the narrow operating range of current used for this procedure. When welding speed was increased, without increasing welding current, cold laps or skips occurred; when welding current was increased, erratic arc action resulted. Much higher currents, such as those used for spray transfer, were not feasible because the sheet was too thin for the energy input.

By changing to short-circuiting transfer, good results were consistently obtained.

Table 4. Typical Depth of Grooves in Backing Bars or Plates Used in Arc Welding of Magnesium Alloys

Base-metal thickness, in.	Depth of groove, in.: Gas tungsten-arc welding	Gas metal-arc welding: No root opening (a)	Gas metal-arc welding: Root opening
0.025	0.015	0.020	0.020
0.040	0.020	0.030	0.020
0.063	0.025	0.040	0.030
0.090	0.030	0.060	0.040
0.125	0.030	0.070	0.040
0.160	0.040	0.070	0.050
0.190	0.040	0.070	0.050
0.250	0.050	0.070	0.060
0.375	0.060	0.080	0.060

(a) With no root opening, grooves in backing bars or plates are deeper to permit better balance between top and bottom weld reinforcement. Use of a root opening permits balancing reinforcement with a shallower groove depth.

Table 5. Preheat Temperatures and Postweld Heat Treatments for Magnesium Alloy Castings

Alloy	Temper of alloy(a): Before welding	Temper of alloy(a): After treatment	Maximum preheat temperature(b), F	Postweld heat treatment(c)
AZ63A	T4	T4	720	½ hr at 730 F
	T4 or T6	T6	720	½ hr at 730 F + 5 hr at 425 F
	T5	T5	500(d)	5 hr at 425 F
AZ81A	T4	T4	750	½ hr at 780 F
AZ91C	T4	T4	750	½ hr at 780 F
	T4 or T6	T6	750	½ hr at 780 F + 4 hr at 420 F(e)
AZ92A	T4	T4	750	½ hr at 770 F
	T4 or T6	T6	750	½ hr at 770 F + 4 hr at 500 F
AM100A	T6	T6	750	½ hr at 780 F + 5 hr at 425 F
EK30A	T6	T6	500(d)	16 hr at 400 F
EK41A	T4 or T6	T6	500(d)	16 hr at 400 F
	T5	T5	500(d)	16 hr at 400 F
EZ33A	F or T5	T5	500(d)	2 hr at 650 F(f) + 5 hr at 420 F
HK31A	T4 or T6	T6	500	1 hr at 600 F(f) + 16 hr at 400 F
HZ32A	F or T5	T5	500	16 hr at 600 F
K1A	F	F	None	None
QE22A	T4 or T6	T6	500	8 hr at 985 F(g) + 8 hr at 400 F
ZE41A	F or T5	T5	600	2 hr at 625 F + 16 hr at 350 F(f)
ZH62A	F or T5	T5	600	2 hr at 625 F + 16 hr at 350 F
ZK51A	F or T5	T5	600	2 hr at 625 F + 16 hr at 350 F(f)
ZK61A	F or T5	T5	600	48 hr at 300 F
	T4 or T6	T6	600	2 to 5 hr at 930 F + 48 hr at 265 F

(a) T4 = solution heat treated; T6 = solution heat treated and artificially aged; T5 = artificially aged; F = as cast. "After treatment" means after postweld heat treatment. (b) Heavy and unrestrained sections usually need no preheat; thin and restrained sections may need preheating up to maximum temperatures shown, to avoid weld cracking. A sulfur dioxide or carbon dioxide atmosphere is recommended when temperature exceeds 700 F. (c) Temperatures shown are maximum allowable; furnace controls should be set so temperature does not exceed indicated maximum. A sulfur dioxide or carbon dioxide atmosphere is recommended when temperature exceeds 700 F. (d) For 1½ hr max. (e) 16 hr at 335 F may be used instead of 4 hr at 420 F. (f) This phase of heat treatment is optional and serves to induce greater stress relief. (g) Quench in water at 140 to 220 F before second heat treatment.

Table 6. Typical Operating Conditions for Gas Metal-Arc Butt Welding of Magnesium Alloys(a)

Base-metal thickness, in.	Type of groove	Number of passes	Electrode: Diameter, in.	Electrode: Feed rate, ipm	Electrode: Consumption, lb/ft of weld	Current, amp	Voltage, v	Argon flow rate, cfh
Short-Circuiting Mode of Metal Transfer								
0.025	Square(b)	1	0.040	140	0.006	25	13	40-60
0.040	Square(b)	1	0.040	230	0.009	40	14	40-60
0.063	Square(b)	1	0.063	185	0.018	70	14	40-60
0.090	Square(b)	1	0.063	245	0.024	95	16	40-60
0.125	Square(c)	1	0.094	135	0.030	115	14	40-60
0.160	Square(c)	1	0.094	165	0.037	135	15	40-60
0.190	Square(c)	1	0.094	205	0.046	175	15	40-60
Pulsed-Arc Mode of Metal Transfer(d)								
0.063	Square(b)	1	0.040	360	0.014	50	21	40-60
0.125	Square(b)	1	0.063	280	0.028	110	24	40-60
0.190	Square(b)	1	0.063	475	0.047	175	25	40-60
0.250	Single-V, 60° (e)	1	0.094	290	0.065	210	29	40-60
Spray-Arc Mode of Metal Transfer(f)								
0.250	Single-V, 60° (e)	1	0.063	530	0.042	240	27	50-80
0.375	Single-V, 60° (e)	1	0.094	285-310	0.057	320-350	24-30	50-80
0.500	Single-V, 60° (e)	2	0.094	320-360	0.106	360-400	24-30	50-80
0.625	Double-V, 60° (g)	2	0.094	330-370	0.125	370-420	24-30	50-80
1.000	Double-V, 60° (g)	4	0.094	330-370	0.208	370-420	24-30	50-80

(a) Welding speed, 24 to 36 in. per minute. (b) Zero root opening. (c) Root opening, 0.090 in. (d) Pulse voltage of 55 volts, except for metal 0.190 in. thick, which uses a pulse voltage of 52 volts. (e) ¹⁄₁₆-in. root face and zero root opening. (f) Settings also apply to fillet welds in the same thickness of metal. (g) ⅛-in. root face and zero root opening.

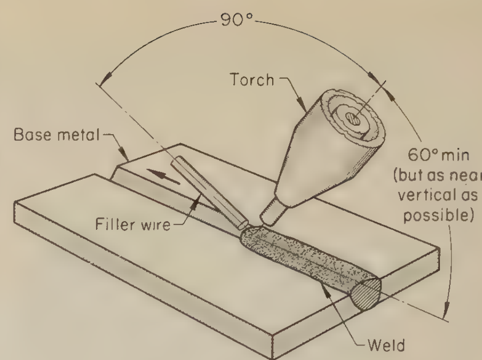


Fig. 2. Angular relations among torch, filler wire, and joint, in gas tungsten-arc welding

This procedure, which is generally recommended for thicknesses up to approximately ³⁄₁₆ in., also resulted in lower welding costs through increased welding speed and lower electrode cost.

A comparison of the welding conditions and deposition costs for the two procedures is given in Table 7. Although higher current was used with short-circuiting transfer than with globular transfer, the current density was much lower because of the increased electrode size.

Welding positions are restricted, by the high deposition rate and fluidity of the weld metal, to flat, horizontal and vertical-up.

Typical operating conditions for gas metal-arc butt welding of magnesium alloys in the thickness range from 0.025 to 1 in. are presented in Table 6. These operating conditions are intended as a guide and should be altered to the extent required by experience with specific applications.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding is used more extensively than gas metal-arc welding for joining magnesium alloys.

Alternating-current machines with a high-frequency current superimposed on the normal welding current for arc stabilization, and direct-current machines with continuous amperage control are used. For thin sheets, both alternating current and reverse-polarity direct current are used. On material over ³⁄₁₆ in. thick, alternating current is preferred, because it provides deeper penetration. Straight-polarity direct current is seldom used on magnesium alloys, because the arc lacks cathodic cleaning action.

Alternating-current machines should be equipped with a primary contactor, actuated by a switch on the torch or by a foot switch, for starting and stopping the arc. Otherwise, the arcing that occurs while the electrode approaches or draws away from the workpiece may result in burned spots on the work.

Pure tungsten, zirconiated, and thoriated electrodes, from 0.010 to 0.250 in. in diameter, are used for gas tungsten-arc welding of magnesium alloys.

Additional information on power supplies, electrodes and related items for the gas tungsten-arc process is given in the article on Gas Tungsten-Arc Welding, pages 113 to 137.

Manual Welding. Data on current settings, electrode diameter, shielding-gas flow, filler-metal diameter, and fill-

er-metal consumption for manual gas tungsten-arc welding of butt joints in magnesium alloys 0.040 to 0.500 in. thick are given in Table 8.

For best results, the electrode should be held close to the work, to produce an arc about 1/32 in. long. The preferred angles of torch, joint and filler metal are given in Fig. 2.

Welding should be done at a uniform speed in a straight line. A weaving or rotary motion should be used only for fillet welds or large corner joints. Forehand welding is preferred. Best practice is to minimize the number of stops. If stops are required, the weld should be restarted on weld metal, about ½ in. from the end of the previous weld.

To minimize the risk of weld cracking, either of the methods shown in Fig. 3 should be used: method A, in which starting and runoff plates (or tabs) are used to start and end the weld; or method B, in which the weld is made in two increments, by passes that begin in the middle and progress toward opposite ends. Also, the base metal (and fixture, if used) should be preheated to at least 200 to 300 F.

If the thickness of the two components to be welded differs by ¼ in. or more, the thicker section should be preheated to approximately 300 F.

Short-Run Production. For short production runs for which the cost of elaborate fixtures cannot be justified, tooling costs can be minimized by fabricating the components so that they can be tack welded into position. The example that follows describes the fabrication of an assembly consisting of 13 components, using tack welds and manual gas tungsten-arc welding.

Example 340. Use of Tack Welding Instead of Fixturing for Short-Run Production (Fig. 4)

To minimize tooling costs on short production runs of electronic deck assemblies, which were essentially two rectangular boxes 2 in. high by 2 in. wide by 4 in. long, as shown in Fig. 4, tack welds were used to position some of the component pieces.

Formed sheet sections of 0.050-in.-thick AZ31B-H24 were tack welded into position by gas tungsten-arc welding, using 1/16-in. ER AZ61A filler wire. The tack welds were ⅛ in. long and were spaced on 2-in. centers (starting at each corner). A tool plate and toggle clamps held the pieces for tack welding. Tack welds were not used to hold angle pieces.

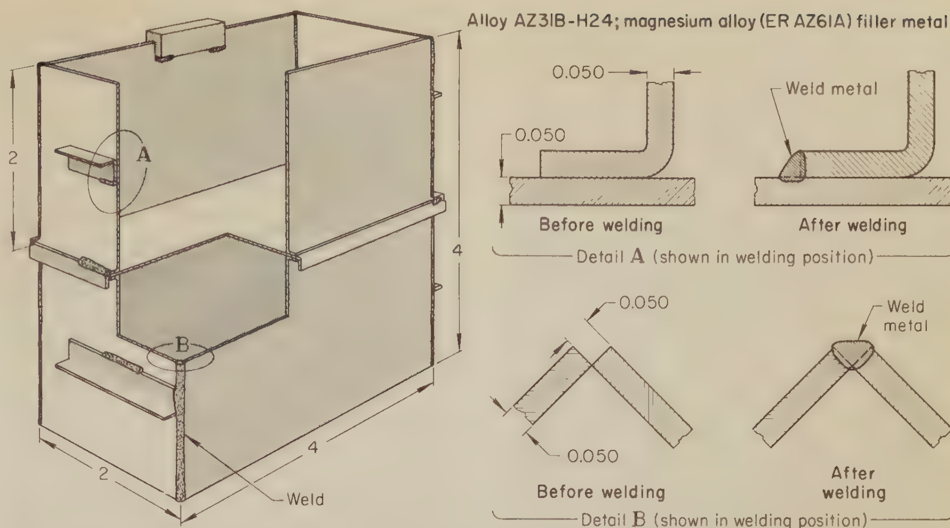
Welding of the assembled and tack welded components was completed by manual gas tungsten-arc welding with 1/16-in.-diam ER AZ61A filler wire. The corner joints were welded with continuous beads about 2 in. long, and the flanged bottom of the top part of the assembly was joined to the sides with 1-in.-long fillet welds. Extruded angle sections were fillet welded to the ends of the boxes with welds about 1 in. long (see detail A in Fig. 4).

The assembly was repositioned manually so that all welds could be made in either the flat or the horizontal position.

A standard alternating-current power supply with a high-frequency arc stabilizer was used.

Helium was selected as the shielding gas because a hotter and more stable arc was produced than would have been possible with argon shielding gas.

Preheating was not used, but after welding, the assemblies were stress relieved at 350 F for 3½ hr to prevent stress-corrosion cracking. Welds were inspected visually.



Conditions for Manual Gas Tungsten-Arc Welding

Joint types ....Lap and corner	Electrode ....0.040-in.-diam EWP
Weld types ....Fillet and single V-groove	Filler metal ....1/16-in.-diam ER AZ61A(a)
Welding positions ....Horizontal and flat	Torch ....350 amp, water cooled(b)
Preweld cleaning ....Wire brushing	Power supply ....300-amp transformer(c)
Preheat ....None	Current, fillet welds ....25 amp, ac
Fixtures ....Tool plate and toggle clamps	Current, V-groove welds ....40 amp, ac
Shielding gas ....Helium, at 25 cfh	Postweld heat treatment ....350 F, 3½ hr

(a) 36-in.-long rod. (b) Ceramic nozzle. (c) Continuous duty, with high-frequency oscillator.

Fig. 4. Electronic deck assembly that was tack welded before the principal welding operation, thus eliminating need for expensive fixturing (Example 340)

Table 7. Cost Comparison of Short-Circuiting and Globular Metal Transfer in Gas Metal-Arc Welding of 0.110-In.-Thick ZE10A-H24 Sheet (Example 339) (a)

Item	Globular transfer	Short-circuiting transfer
Joint type	Butt	Butt
Root opening, in.	None	0.090
Weld type	Square groove	Square groove
Electrode	1/16-in.-diam ER AZ61A	3/32-in.-diam ER AZ61A
Electrode-feed rate, ipm	300	160
Current (dcrp), amp	135	175
Voltage, v	26	17
Shielding gas	Argon, at 50 cfh	Argon, at 50 cfh
Welding speed, ipm	32	39
Electrode consumption, lb/ft of weld	0.02236	0.02293
Cost per foot of weld(b)	$0.263	$0.214

(a) Comparison based on automatic single-pass welding of 58-in.-long joints in the flat position. (b) Cost factors: Argon, $0.10 per cu ft; labor, $3.00 per hour; overhead, 150% of direct labor cost; operating factor, 33%; 1/16-in.-diam electrode, $4.04 per lb; 3/32-in.-diam electrode, $3.28 per lb.

Table 8. Conditions for Manual Gas Tungsten-Arc Welding of Butt Joints in Magnesium Alloys

Base-metal thickness, in.	Joint design(a)	No. of passes	Electrode diameter, in.	Current (ac), amp(b)	Argon flow rate, cfh	Filler metal: Diameter, in.	Filler metal: Consumption, lb/ft of weld
0.040	A	1	1/16	35	12	3/32	0.004
0.063	A	1	3/32	50	12	3/32	0.005
0.080	A	1	3/32	75	12	3/32	0.006
0.100	A	1	3/32	100	12	3/32	0.008
0.125	A	1	3/32	125	12	⅛	0.009
0.190	A	1	⅛	160	15	⅛	0.011
0.250	B	2	5/32	175	20	⅛	0.026
0.375	B	3	5/32	175	20	5/32	0.057
0.375	C	2	3/16	200	20	⅛	0.024
0.500	C	2	3/16	250	20	⅛	0.047

(a) A = square-groove butt joint, zero root opening; B = 60°-bevel, single-V-groove butt joint, 1/16-in. root face, zero root opening; C = 60°-bevel, double-V-groove butt joint, 3/32-in. root face, zero root opening. (b) Thorium-containing alloys will require about 20% higher current. With helium shielding, required welding current will be reduced by about 20 to 30 amp.

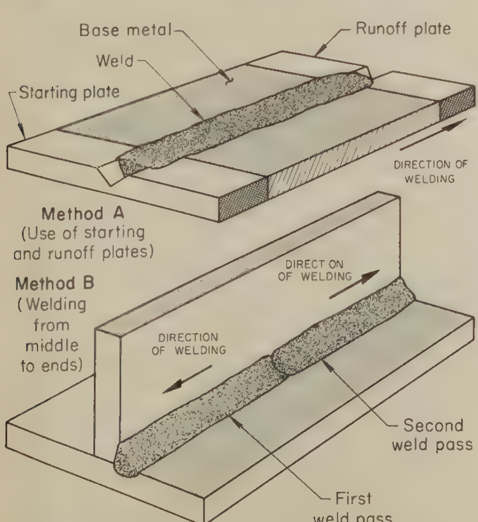


Fig. 3. Two methods of welding magnesium alloys that help to prevent weld cracking

In the three examples that follow, manual welding was used.

Examples 341 to 343. Three Types of Joints Welded Manually (Table 9)

Example 341 — T-Joint. The welding of a single ⅛-in. fillet in an 8-in.-long T-joint between sheets of alloy AZ31B ¹⁄₁₆ and ⅛ in. thick (see Table 9) was used as a quick shop test for welder qualification. The welder adjusted the machine settings, gas flow and welding speed suitable for producing a sound weld with proper contour and adequate penetration, using manual gas tungsten-arc welding. After welding, the joint was broken by striking a blow against the unwelded side of the vertical stem so as to open and expose the root of the weld. The fracture was then examined for depth of penetration, porosity, lack of fusion, and other defects. Welding conditions and a view of the joint are given in Table 9.

Example 342 — Single-V-Groove Butt and Corner Joints. Structural frames were fabricated by welding the mitered ends of 1-by-1-by-³⁄₁₆-in. angles extruded from alloy AZ31B. One of the four right-angle corners of one of these structural frames is shown in Table 9. Manual gas tungsten-arc welding was used because production quantity was less than 50 pieces per month.

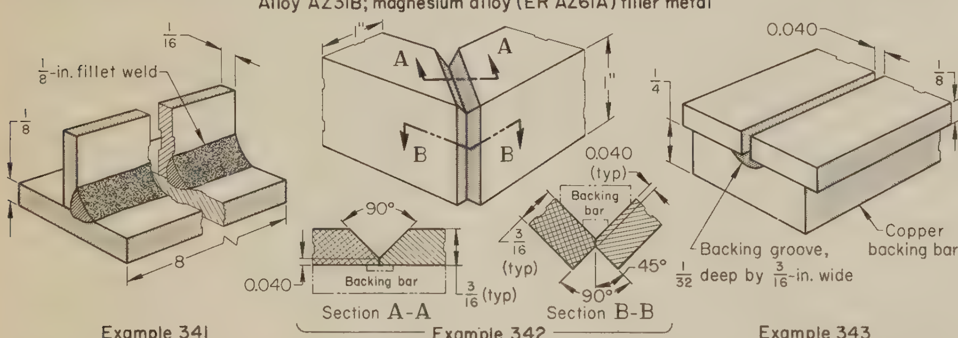
Procedure consisted of mitering, edge beveling, cleaning, assembling on a fixture, and welding. Horizontal joint edges were beveled 45° with a 0.040-in.-deep root face; vertical joint edges were beveled to form a similar root face for a 90° corner joint. After acid pickling and rinsing, the angles were assembled on a clamping fixture provided with flat backing bars for the horizontal joints and with corner backing bars for the vertical joints. The backing bars for both the horizontal and the vertical joints were provided with backing grooves that were ⅛ in. wide by 0.020 in. deep. The outside corner joint was single-pass welded, vertical-up; the grooved butt joint was single-pass welded in the flat position. No preheat was used, but the frames were postweld stress relieved at 350 F for 1½ hr. Welding conditions are given in Table 9.

Example 343 — Square-groove-welded butt joints (with 0.040-in. root opening) in ⅛-in.-thick AZ31B-H24 sheet were originally to be gas metal-arc welded, but contact-tube arcing occurred and contamination of the filler metal resulted. Rather than delay production while the arcing problem was being eliminated, it was decided to use manual gas tungsten-arc welding instead of gas metal-arc. Good mechanical properties were obtained in single-pass welds, using argon shielding on the torch side and a grooved copper backing bar, but no gas backing, on the underside. Joint alignment was maintained with bolted hold-down bars. Other welding details are given in Table 9.

Table 9. Manual Gas Tungsten-Arc Welding of Alloy AZ31B (Examples 341 to 343) (a)

Item	Example 341	Example 342	Example 343
Joint type	T	Corner; butt	Butt
Weld type	Single fillet	Single-V groove	Square groove
Welding position	Horizontal	Vertical-up; flat	Flat
Shielding gas and flow rate	Argon; 18 cfh	Argon; 18 cfh	Argon; 18 cfh
Electrode (EWP) diameter	³⁄₃₂ in.	⅛ in.	⅛ in.
Filler-metal (ER AZ61A) diameter	¹⁄₁₆ in.	³⁄₃₂ in.	¹⁄₁₆ in.
Current (ac, HF-stabilized)	110 amp	125 amp	135 amp
Welding speed	10 ipm	5 pcs per hr (b)	10 ipm
Postweld heat treatment	500 F, 15 min	350 F, 1½ hr	350 F, 1½ hr

Alloy AZ31B; magnesium alloy (ER AZ61A) filler metal



(a) A 300-amp ac/dc power supply with continuous high frequency was used for all three applications, with a light-duty water-cooled welding torch. All workpieces were preweld cleaned by chromic-sulfuric pickling. No preheat was used. (b) Includes fixturing, welding and unloading.

Table 10. Operating Conditions for Automatic Gas Tungsten-Arc Welding of Butt Joints in Two Magnesium Alloys (a)

Type of current	Current, amp	Diameter of tungsten electrode, in.	Arc length, in.	ER AZ61A or ER AZ92A filler metal, 0.063-in. diameter — Feed rate, ipm	Consumption, lb/ft of weld	Travel speed, ipm
AZ31B, 0.063 In. Thick						
Alternating, balanced wave	55	0.094	0.025	35	0.007	12
	60	0.094	0.025	50	0.005	24
	70	0.125	0.025	54	0.004	36
	95	0.125	0.025	96	0.005	45
	170	0.188	0.025	160	0.005	70
	195	0.188	0.025	190	0.006	80
	200	0.188	0.025	203	0.005	95 (b)
Direct, straight polarity	75	0.125	0.025	80	0.004	48
Direct, reverse polarity	120	0.250	0.020	184	0.005	80 (b)
AZ31B, 0.190 In. Thick						
Alternating, balanced wave	300	0.250	0.020	159	0.011	34 (b)
Direct, straight polarity	170	0.125	0.030	70	0.008	20 (b)
Direct, reverse polarity	120	0.250	0.020	10 (c)	0.008 (c)	7 (b)
ZE10A, 0.250 In. Thick						
Alternating, balanced wave	460	0.250	0.010	180	0.020	22

(a) With helium shielding for AZ31B, and argon for ZE10A; flow rate, 20 cfh. (b) Maximum speed limitation because of undercutting or arc instability. (c) Diameter of filler metal, 0.094 in.

Automatic welding of magnesium alloys by the gas tungsten-arc process is similar to manual welding, except that higher currents and welding speeds are used. The data in Table 10 can be used as a guide to determine settings for automatic welding. Alternating current is best, although reverse-polarity direct current can be used. A balanced-wave alternating-current machine, or a conventional alternating-current machine equipped with a battery bias for wave balancing, should be used.

Constant alignment of electrode and filler metal is important in automatic welding. Filler metal is fed into the arc at a low angle to the work, so that the filler rod touches the weld surface just ahead of the electrode. The arc length shown in Table 10 should be preset and maintained.

Travel speeds up to 95 in. per minute can be used on thin sheet, but 24 to 36 in. per minute is more common.

Automatic welding is not necessarily restricted to high-production applications; sometimes the high degree of control that can be attained with automatic welding is required regardless of quantity. A low-production application is described in the next example.

Example 344. Extrusions Joined to Sheet by Automatic Welding (Fig. 5)

Airtight doors for an aerospace application were made by welding panels of alloy AZ31B-H24 sheet to frames extruded from alloy AZ31B. The frames, which acted as stiffeners, also contained a groove for an air seal. Cross sections of similar offset-butt joints in two designs of door assemblies are shown as joints A and B in Fig. 5. The offset lip of the extruded frames provided a single-bevel-groove butt joint and supplied backing for the weld; the lap joint on the underside was not welded.

Although production quantities were low, automatic gas tungsten-arc welding was used, because weld quality was good and the equipment was available. Automatic travel was obtained by mounting the welding equipment on the motorized carriage of a cutting machine. Differences in welding conditions for the two joints (see table with Fig. 5) resulted from operator choice or judgment. Both procedures produced satisfactory welds, but the difference in welding speeds would have been significant had production quantities been large.

Repair Welding of Castings

A significant portion of the total amount of welding that is done on magnesium alloy castings is for repair.

The type, size and location of defects in castings vary so much that each repair job presents its own welding problems; procedures cannot be standardized. However, most repairs are subject to the general procedures that follow:

1. The casting must be stripped of paint, and the effects of chrome pickling must be removed at broken edges and around cracks, with steel wool or with a power wire brush having stainless steel bristles.
2. The casting should be clamped in place and the surface adjoining the fracture should be beveled for the weld (see illustrations with Table 3).
3. Preheating, if necessary, should be done at the temperatures recom-

mended in Table 5. Either local heating with a torch or furnace heating can be used. The use of a protective atmosphere during furnace heating will reduce the possibility of oxidation at temperatures above 700 F.

4 Welding should be done immediately after preheating. Reheating may be necessary if the temperature of the casting drops significantly below the preheat temperature.

5 Medium-size weld beads should be used.

6 Welding should progress from the center of the break to the outside edges. The arc should not be allowed to dwell too long in any one area, because weld cracking may result.

7 A foot control should be used to fade out the arc gradually so as to minimize thermal shock from arc stops. Thermal shock may cause cracking.

Examples of Repair Welding. The seven examples that follow describe procedures that were used in successful repair welding of specific castings.

Example 345. Repair of Sand Holes in a Wheel-Rim Casting (Fig. 6)

After machining, aircraft wheel-rim castings of AZ91C-T4 were occasionally found to have small sand holes (Fig. 6). Defects of a size that could be removed by cutting a groove about ⅛ in. deep and ½ in. wide were repaired by welding, following the procedure described below.

The defective area was cleaned out by cutting a smoothly blended groove (see "Before welding" in Fig. 6), using a burring tool. After complete removal of defective material was verified by dye-penetrant inspection, the groove and surrounding area were wire brushed to prepare for gas tungsten-arc welding.

The relatively thick section of the casting in the repair area and the wide groove for the deposit ensured that the weld would be under low restraint; therefore, preheating was not necessary. Ordinarily, a standard filler metal, such as ER AZ92A or ER AZ101A, would prove satisfactory for welding the AZ91C base metal, but in this application, a filler metal of the same composition as the base metal was specified.

The weld was made by striking the arc at the bottom of the groove and proceeding in a circular direction along the groove wall to fill the groove, as shown in the "After welding" view in Fig. 6. Welding conditions are given in the table with Fig. 6.

After welding, the weld reinforcement was ground to ⅓₂ in. above the base-metal surface and surface weld quality was verified by dye-penetrant inspection. After passing inspection, the casting was heat treated to the T6 condition. The casting was accepted after radiographic inspection indicated satisfactory internal weld quality.

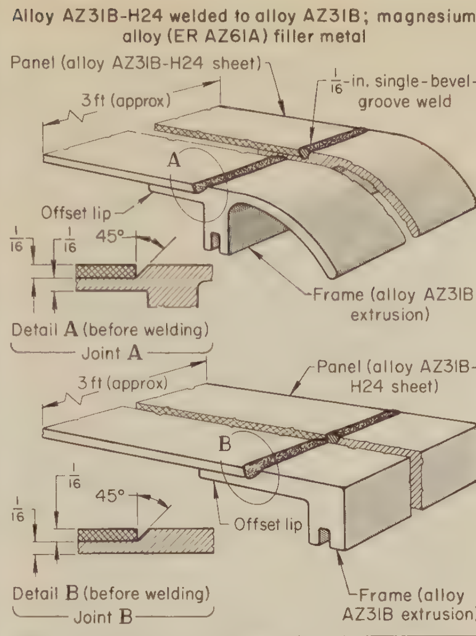
Example 346. Repair of a Defect in a Partly Machined Casting (Fig. 7)

Small defects in cast AZ91C-T6 alloy oil sumps for aircraft engines were caused by core shifts or other errors in the foundry. Sometimes, such defects were not detected until after considerable machining had been done on the part. Local surfacing by the gas tungsten-arc method was accepted as a means of salvaging such parts.

A typical casting error that qualified as repairable was an undersize wall thickness, shown in Fig. 7. The defect, which was discovered after most of the machining had been completed, covered an area less than 2 sq in. and was in a low-stress region.

The casting had been given a dichromate treatment to remove surface oxide film, and therefore thorough preweld cleaning was required. The casting was vapor degreased with trichlorethylene, and the surface of the area to be welded was further cleaned by brushing with a stainless steel wire brush. Preheating was not needed.

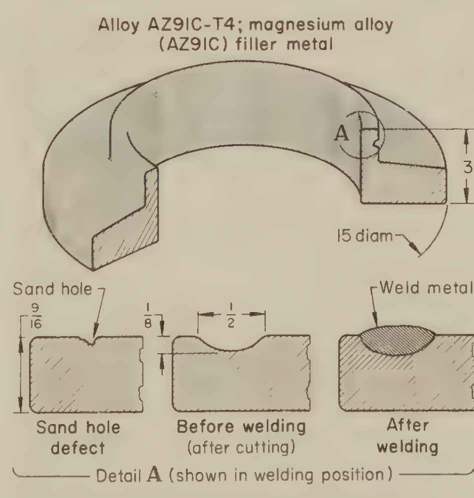
The casting was positioned on a welding table in the flat position and welded in two



Automatic Gas Tungsten-Arc Welding

Joint type	Offset butt
Weld type	Single-bevel groove
Preweld cleaning	Chromic-sulfuric pickle
Welding position	Flat
Preheat	None
Shielding gas	Argon, at 18 cfh, for joint A; argon, at 16 cfh, for joint B
Electrode	⅛-in.-diam EWP
Filler metal	1⁄16-in.-diam ER AZ61A
Torch	Water cooled
Power supply	300 amp ac (HF-stabilized)
Current (ac)	175 amp for joint A, 135 amp for joint B
Wire-feed rate	65 ipm
Travel speed	20 ipm for joint A, 15 ipm for joint B
Postweld heat treatment	350 F for 1½ hr

Fig. 5. Two similar joints in different door assemblies that were welded under slightly different conditions (Example 344)



Manual Gas Tungsten-Arc Welding

Weld type	Surfacing, for repair
Welding position	Flat
Preheat	None
Shielding gas	Helium, at 20 cfh
Electrode	3⁄32-in.-diam EWP
Filler metal	⅛-in.-diam AZ91C
Torch	300 amp, water cooled
Power supply	300-amp transformer, with high-frequency generator
Current	60 amp, ac
Postweld heat treatment	780 F for ½ hr plus 420 F for 4 hr

Fig. 6. Aircraft wheel-rim casting that was salvaged by repair welding of sand holes (Example 345)

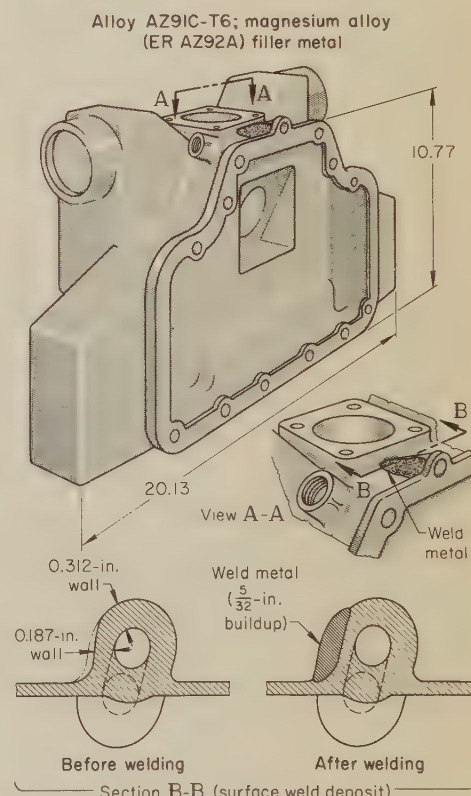
passes under the conditions listed in the table with Fig. 7. Because too much heat input could cause burn-through or weld cracking, and too little could result in porosity, good welding skill was required. The use of a foot-operated control was an aid in regulating welding current for heat input and for obtaining a smoothly blended weld contour. The weld was brushed with a stainless steel wire brush after each pass.

The repaired casting was stress-relieved for 1 hr at 500 F in a furnace, to avoid possible stress corrosion. Finishing of the completed weld was not required, as there was no reason to conceal the repair. A spot radiographic inspection was made to check for porosity, tungsten inclusions, and general weld soundness.

Example 347. Repair of a Crack in a Jet-Engine Casting (Fig. 8)

During an aircraft jet-engine overhaul, fluorescent-penetrant inspection revealed a 2½-in.-long crack near a rib in the cast AZ92A-T6 compressor housing shown in Fig. 8. The thickness of the section containing the crack ranged from 3⁄16 to 5⁄16 in. Repair welding was permissible.

The part was vapor degreased to remove surface grease and dirt and soaked in a commercial, alkaline paint remover. The crack was then marked with a felt-tip marker, and the part was stress relieved at 400 F for 2 hr.



Manual Gas Tungsten-Arc Welding

Weld type	Surfacing, for repair
Welding position	Flat
Number of passes	Two
Preheat	None
Shielding gas	Argon, at 13 to 15 cfh
Electrode	3⁄32-in.-diam EWP
Filler metal	3⁄32-in.-diam ER AZ92A
Torch	300 amp, water cooled(a)
Power supply	400-amp transformer, with high-frequency starting
Current	10 to 85 amp, ac(b)
Arc length	1⁄16 to ⅛ in.
Postweld stress relief	500 F for 1 hr (furnace)

(a) Ceramic nozzle, ½ in. (b) Current was regulated by foot switch.

Fig. 7. Oil-sump casting for an aircraft engine that was repair welded to increase wall thickness (Example 346)

The crack was removed by slotting the flange through to the periphery (see Fig. 8). Each side of the slot was beveled to approximately 30° from vertical to form a 60° double-V groove. The area to be welded was cleaned with a power wire brush with stainless steel bristles.

Welding was done by the manual gas tungsten-arc process, without preheating, under the conditions listed with Fig. 8.

The welding technique consisted in maintaining a low-amperage arc (less than 70 amp) directed onto the base metal while filler metal was deposited on the sides of the groove, working from the innermost point outward. After a weld puddle formed, the arc was weaved slightly while depositing a bead on the sides of the groove. During welding, heat input was adjusted by a foot-operated current-control rheostat, to maintain a uniform weld puddle.

After welding was completed on one side of the slot, the casting was turned over. Excess drop-through and areas of incomplete penetration were removed by grinding. The underside was then welded by the same technique used for the first side.

After welding, the casting was stress relieved at 400 F for 2 hr, and inspected by the fluorescent-penetrant method.

Example 348. Correction of a Machining Error (Fig. 9)

After machining an AZ92A-T6 alloy aircraft-engine oil sump, it was found that six stud holes had been spotfaced 0.093 in. deeper than specified, as shown in Fig. 9. The affected areas were small and well spaced. The casting was subject to low stress in service, and although the defective areas were located on a bolting flange that was subject to stresses from bolting, there was no other loading of consequence on the affected areas. Therefore, the part was judged repairable by welding.

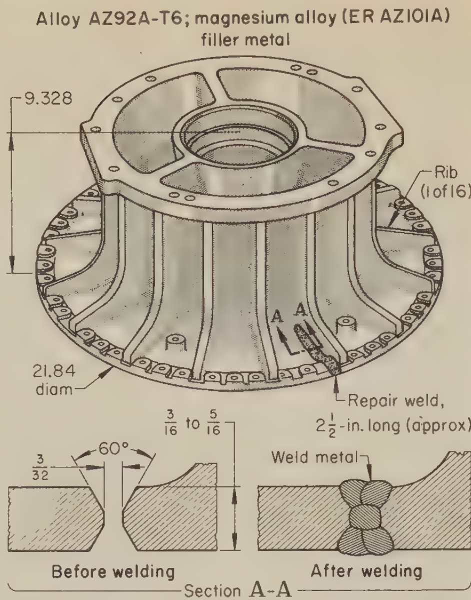
As a precaution, to minimize any possibility of cracking, the casting was preheated and heat input during welding was reduced. The preheating was done in a furnace at 450 to 500 F for 1 hr, after which the entire casting was kept wrapped in an asbestos blanket, except for the one boss area at a time that was exposed for welding. After completing each weld, the workpiece temperature was checked with a temperature-indicating crayon, and if temperature had dropped below 400 F, the piece was reheated before welding was resumed.

To reduce heat input, the torch was fitted with a 1/16-in.-diam tungsten electrode and a 3/8-in.-diam ceramic cup which delivered argon gas at 15 cu ft per hour. Initial current setting was 65 amp, which, by means of a foot-operated control, was varied from 10 to 65 amp, as required. Figure 9 shows the weld deposit, with allowance for machining. Details of other welding conditions are given in the table with Fig. 9. All other operations, including preweld cleaning, and inspection, were the same as those described in Example 346.

Examples 349 to 351. Gas Tungsten-Arc Repair Welding of Sand Castings (Fig. 10)

Figure 10 shows three sand castings that represent typical applications of manual gas tungsten-arc welding for the correction of surface flaws that occur in machining, of defects resulting from the casting process, and of deficiencies in design. As shown in the table that accompanies Fig. 10, welding was done with high-frequency-stabilized alternating current.

The castings were preheated and maintained at temperature during welding, to avoid weld cracking. The postweld heat treatments shown in the table are a compromise between stress relieving and an aging treatment, to avoid distortion. However, when repair welded areas were large enough so that the heat of welding caused a significant reduction in mechanical properties of the casting, welding was followed by a full heat treatment. For all three of the castings shown in Fig. 10, radiographic inspection was used in establishing the

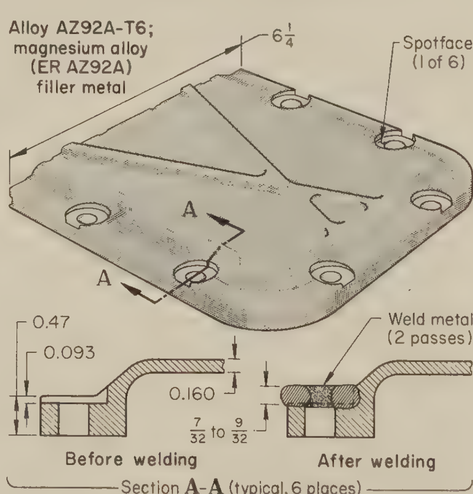


Manual Gas Tungsten-Arc Welding

Joint type	Butt
Weld type	60° double-V-groove repair
Shielding gas	Argon, at 20 cfh(a)
Electrode	1/16-in.-diam EWTh-2
Filler metal	1/16-in.-diam ER AZ101A
Torch	Water cooled
Power supply	300-amp transformer, with high-frequency starting
Current	Under 70 amp, ac(b)
Postweld stress relief	400 F for 2 hr(c)
Inspection	Fluorescent penetrant

(a) Also used for backing. (b) Current was regulated by a foot switch. (c) Also preweld.

Fig. 8. Cast inlet compressor housing that was salvaged by welding after service in a jet engine (Example 347)



Manual Gas Tungsten-Arc Welding

Weld type	Surfacing, for repair
Welding position	Flat
Number of passes	Two
Preheat in furnace	450 to 500 F for 1 hr(a)
Shielding gas	Argon, at 13 to 15 cfh
Electrode	1/16-in.-diam EWP
Filler metal	3/32-in.-diam ER AZ92A
Torch	300-amp, water cooled(b)
Power supply	400-amp transformer, with high-frequency starting
Current	10 to 65 amp, ac
Postweld stress relief	500 F for 1 hr (furnace)

(a) Casting was wrapped in asbestos blanket during welding. (b) Ceramic cup, 3/8 in.

Fig. 9. Section of an oil-sump casting for an aircraft engine that was salvaged by repair welding six spot-facing areas that had been machined undersize (Example 348)

welding procedure, and all repair welds were subjected to fluorescent-penetrant inspection. Fillet welds were left as welded; other types of welds were finished to conform to the contour of the casting or to desired shape.

Example 349 — Repairing of a Machining Scratch. The views at the top in Fig. 10 show a portion of an alloy AZ92A-T6 sand casting with a machining scratch, ¼ in. long and 0.030 in. deep, that was repaired by gas tungsten-arc surface welding, under the conditions given in the table with Fig. 10. Machining flaws up to 3/8 in. square, in castings of various shapes and sizes, have been corrected by this method.

Example 350 — Welding a Patch for Correction of Wall Thinning Due to Core Shift. The middle views in Fig. 10 show a flanged cylindrical alloy EZ33A sand casting that was one of about 200 such castings in which core shift caused the ¼-in. wall to thin to ⅛ in., beginning about 1 in. away from one of the flanges. To repair these thin areas without distortion of the cylinder, a 3-by-4-in. piece of ¼-in. alloy HK31A plate was formed to fit the outside wall of the cylinder, drilled in the center with a ½-in.-diam hole, and clamped in place over the thin area. The patch was tack welded at the four corners, and then gas tungsten-arc welded along the periphery with intermittent ¼-in. fillet welds 1 in. long. During welding, the inside of the cylinder was flushed with helium to prevent oxidation of heated portions.

After the patch had been fillet welded to the cylinder, the center hole was plug welded, using successive small beads to ensure fusion to the wall of the casting, and to minimize the possibility of cracking, which can occur when large beads are deposited. The part was then finish machined, using plates to hold the flanges. Welding conditions are given in the table with Fig. 10.

Example 351 — Applying an All-Weld-Metal Boss to a Flange. Because a design change was made after the first run of flanged, cylindrical alloy EZ33A castings had been produced, a boss had to be added to one of the flanges on each casting, as shown in the views at the bottom in Fig. 10. Using a buildup welding procedure of successive small beads, a cylindrical boss 1 in. in diameter by ¼ in. high was produced on the flange by manual gas tungsten-arc welding, under the conditions given in the table with Fig. 10. In later production, the pattern was changed, and the boss was cast integrally with the flange.

Defects in repair welds and their causes are discussed in the following paragraphs.

Oxide inclusions are caused by welding on unsound base metal, by inadequate cleaning of base metal or filler metal, by maintaining too long an arc, by insufficient flow of shielding gas, by leaky gas connections, and by defective shielding-gas hoses that allow air to be drawn in.

Tungsten inclusions are caused by maintaining too long an arc, by using too high a current, and by touching the weld puddle, base metal or filler metal with the electrode.

Porosity is usually caused by welding on unsound base metal, by poor preweld cleaning of base metal or filler metal, and by contamination of the shielding gas.

Microshrinkage, a defect consisting of interdendritic voids detectable on magnification, is caused by too rapid current decay at the end of a weld, which results in too rapid freezing of the weld puddle. As a result, the weld puddle is unable to serve as a riser to feed the solidifying weld metal below.

Base-metal cracks are usually caused by excessive heat input or by carrying the arc too far over onto the base-metal surface during repair welding.

Heat Treatment After Welding

Heat treated castings are often heat treated again after welding. The heat treatments shown in Table 5 depend on the temper before welding and that required after welding. Only the minimum heat treating time (½ hr) for complete solution is used for welded AZ81A, AZ91C and AZ92A castings, so as to avoid abnormal grain growth in the deposited weld metal. As noted in Table 5, some solution treatments require an SO_2 or CO_2 atmosphere.

If complete solution treatment is not required, magnesium castings containing more than 1.5% aluminum should always be stress relieved to prevent corrosion cracking in service. Postweld stress-relieving temperatures and times are given in Table 11.

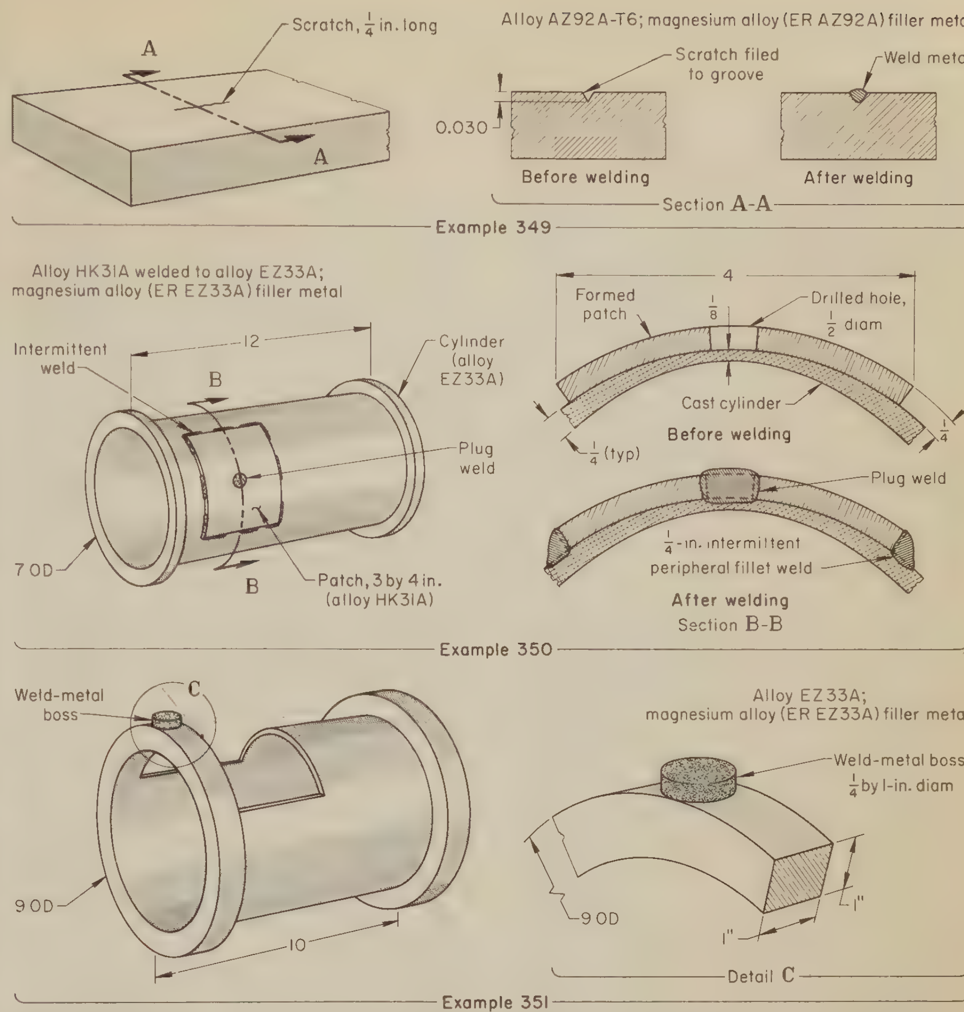
Summary of Examples

Table 12 summarizes the welding conditions used for the 13 examples of practice described in this article.

Table 11. Postweld Stress-Relief Treatments for Magnesium Alloys(a)

Alloy	Temperature, F	Time, min
Sheet		
AZ31B-O(b)	500	15
AZ31B-H24(b)	300	60
HK31A-H24	600	30
HM21A-T8	700	30
HM21A-T81	750	30
ZE10A-O	450	30
ZE10A-H24	275	60
Extrusions		
AZ10A-F	500	15
AZ31B-F(b)	500	15
AZ61A-F(b)	500	15
AZ80A-F(b)	500	15
AZ80A-T5(b)	400	60
HM31A-T5	800	60
Castings(c)		
AM100A	500	60
AZ63A	500	60
AZ81A	500	60
AZ91C	500	60
AZ92A	500	60

(a) Treatments given will produce approximately 80 to 95% stress relief in all alloys except HM31A-T5, where 70% stress relief will be provided. (b) Requires postweld heat treatment to avoid stress-corrosion cracking. (c) Requires postweld heat treatment for maximum strength (see Table 5 for postweld heat treatments).



Welding condition	Example 349	Example 350	Example 351
Conditions for Manual Gas Tungsten-Arc Welding(a)			
Fixtures	None	Plates	None
Welding position	Flat	Flat	Flat
Shielding gas	Argon; 20-24 cfh	Argon; 24-28 cfh(b)	Argon; 24-28 cfh
Electrode (⅛-in. diam)	EWP	EWP	EWP
Filler metal (1/16-in. diam)	ER AZ92A	ER EZ33A	ER EZ33A
Current (ac, hf-stabilized)	80-140 amp	160-180 amp	160-180 amp
Preheat and interpass temperature	250 F	300 F	250-350 F
Postweld heat treatment	300 F, 3 hr	400 F, 2 hr	300 F, 4 hr
Total time per piece(c)	½ hr	2 hr	½ hr

(a) For all three applications, preweld cleaning was done with a wire brush or a rotary file, power supply was a 300-amp transformer with high-frequency (balanced-wave) stabilizer, and electrode holder was a 300-amp water-cooled type. (b) Helium at 8 cfh was used for backing. (c) Not including time for postweld heat treatment.

Example 349: Part of an AZ92A-T6 casting on which a small machining scratch was filed to a groove and surface welded. **Example 350:** Flanged EZ33A casting onto which an HK31A patch was fillet and plug welded, to build up a wall that was thin as the result of core shift. **Example 351:** Cylindrical EZ33A casting on one flange of which a boss, added in a design change, was built up of weld metal deposited in successive passes, each depositing a small amount of filler metal.

Fig. 10. Sand castings repaired by manual gas tungsten-arc welding (Examples 349, 350, 351)

Table 12. Summary of Welding Conditions From Examples in This Article

Example No.	Magnesium alloy	Product forms	Filler metal	Purpose of welding	Shielding gas	Preheat	Postheat Temperature, F	Postheat Time, hr
Gas Metal-Arc Welding (dcrp)								
339	ZE10A-H24	Sheet	ER AZ61A	Joining	Argon	...	...	...
Gas Tungsten-Arc Welding (ac)								
340	AZ31B-H24	Sheet, extrusion	ER AZ61A	Joining	Helium	None	350	3½
341	AZ31B	Sheet	ER AZ61A	Joining	Argon	None	500	¼
342	AZ31B	Extrusion	ER AZ61A	Joining	Argon	None	350	1½
343	AZ31B-H24	Sheet	ER AZ61A	Joining	Argon	None	350	1½
344	AZ31B-H24; AZ31B	Sheet, extrusion	ER AZ61A	Joining	Argon	None	350	1½
345	AZ91C-T4	Casting	AZ91C	Repair	Helium	None	780, ½ hr; plus 420, 4 hr	
346	AZ91C-T6	Casting	ER AZ92A	Repair	Argon	None	500	1
347	AZ92A-T6	Casting	ER AZ101A	Repair	Argon	None	400	2
348	AZ92A-T6	Casting	ER AZ92A	Repair	Argon	450-500 F	500	1
349	AZ92A-T6	Casting	ER AZ92A	Repair	Argon	250 F	300	3
350	HK31A; EZ33A	Sheet, casting	ER EZ33A	Repair	Argon	300 F	400	2
351	EZ33A	Casting	ER EZ33A	Repair	Argon	250-350 F	300	4

Arc Welding of Nickel Alloys

THE WROUGHT NICKEL ALLOYS listed in Table 1 can be arc welded under conditions similar to those used in the arc welding of austenitic stainless steel. Cast nickel alloys, particularly those of high silicon content, present difficulties in welding. The arc welding of heat-resisting nickel alloys is described in the article on Arc Welding of Heat-Resisting Alloys, beginning on page 277 in this volume.

The most widely employed processes for welding the non-age-hardenable (solid solution) wrought nickel alloys are gas tungsten-arc, gas metal-arc, and shielded metal-arc welding. Submerged-arc welding has limited applicability. The gas tungsten-arc process is preferred for welding the precipitation-hardenable alloys, although gas metal-arc and shielded metal-arc welding are also used.

Preweld Heating and Heat Treating. Preweld heating of wrought alloys is not required unless the base metal is below 60 F, in which case a path 10 to 12 in. wide on both sides of the joint should be warmed to 60 to 70 F to avoid condensation of moisture, which might cause porosity in the weld metal. Cast alloys should be heated to 200 to 400 F, depending on the mass of the casting at the joint.

Nickel alloys are usually welded in the solution-treated condition. Precipitation-hardenable alloys should be annealed before welding if they have been severely formed (see the section in this article on Welding of Precipitation-Hardenable Alloys).

Postweld Treatment. No postweld treatment, either thermal or chemical, is needed or recommended to maintain or restore corrosion resistance. Heat treatment may be necessary to meet specification requirements, such as stress relief of a fabricated structure to avoid stress-corrosion cracking of the weldment in hydrofluoric acid vapor or caustic soda, or age hardening (see the section in this article on Welding of Precipitation-Hardenable Alloys).

Cleaning of Workpieces

Nickel and nickel alloys are susceptible to embrittlement by lead, sulfur, phosphorus and some low-melting-point metals. These materials may be present in grease, oil, paint, marking crayons, marking inks, forming lubricants, cutting fluids, shop dirt, and processing chemicals. Before workpieces are heated or welded, they must be completely free of foreign material. Both sides of the workpiece in the area that will be heated by the welding operation should be cleaned. When no subsequent heating is involved, the cleaned area may be restricted to 2 in. on each side of the joint.

Shop dirt, oil and grease can be removed by vapor degreasing or by swabbing with acetone or other nontoxic solvent. Paint and other materials that are not soluble in degreasing solvents may require the use of methylene chloride, alkaline cleaners, or special proprietary compounds. If alkaline cleaners containing sodium sesquisilicate or sodium carbonate are used, the cleaners themselves must be removed prior to welding; spraying or scrubbing with hot water is recommended. Marking ink can usually be removed with alcohol. Processing material that has become embedded in the work metal can be removed by grinding, abrasive blasting, and swabbing with a 10% (by volume) hydrochloric acid solution, followed by a thorough water wash. (Further information on the cleaning of nickel and nickel alloys is given in Volume 2 of this Handbook, beginning on page 661.)

Oxide must also be removed from the area involved in the welding operation, largely because of the difference in melting point between the oxide and the base metal. Oxide can usually be removed by wire brushing.

Joint Design

Various joint designs are used in the arc welding of nickel alloys. The same design can be used for gas tungsten-arc welding and for shielded metal-arc welding. Joint design requires special consideration in gas metal-arc and submerged-arc welding, as discussed in the sections in this article on these two processes. A joint design developed for other metals is not necessarily suitable for nickel alloys, and should not be used unless proved satisfactory by experience or by tests.

Beveled Joints. Beveling is usually not required for metal 0.093 in. or less in thickness, although thinner sections of certain alloys sometimes are beveled (see Table 2). Metal thicker than 0.093 in. should be beveled to form a V, U or J-groove, and should be welded using a backing, unless it is welded from both sides. Otherwise, erratic penetration will result, leading to crevices and voids that will be potential areas of joint weakness and accelerated corrosion in the underside of the joint. For the best underbead contour on joints that cannot be welded from both sides, gas tungsten-arc welding should be used for the root pass.

For metal more than ⅜ in. thick, a double-U-groove or double-V-groove design is preferred. The added cost of preparation is justified because less welding time and material are needed and less residual stress will be developed than with a single-groove design.

Beveling is done best by machine, usually a plate planer or other machine tool. Plasma-arc and electric-arc cutting can be used for joint preparation, but all oxidized metal must be removed from the joint area by grinding or chipping for a depth of $\frac{1}{32}$ to $\frac{1}{16}$ in.

Corner and lap joints may be welded where service stresses will not be high. These joints should be avoided if service temperatures are high or if service conditions involve thermal or mechanical cycling. When corner joints are used, a full-penetration weld must be made, usually with a fillet weld on the root side. Lap joints should be welded on both sides.

Design Considerations. Unlike steel weld metal, molten nickel alloy weld metal does not flow. This characteristic cannot be compensated by extra heat input or by puddling, because serious loss of residual deoxidizers may result.

For joints in metal up to ⅝ in. thick, ample accessibility will be provided by V-groove butt joints beveled to an 80° groove angle. For thicker work metal, U-groove butt joints machined to a 15° bevel angle and a $\frac{3}{16}$ to $\frac{5}{16}$-in. radius are used (see Table 3 in the article on Arc Welding of Heat-Resisting Alloys, page 280). Single bevels used to form T-joints should have an angle of 45°. The bottom radius of a J-groove for T-joints should be at least ⅜ in. and the bevel angle should be about 15°. A root face of ⅛ in. should be used for J-grooves and U-grooves.

Welding Fixtures

Proper fixturing and clamping will hold the workpieces firmly in place, minimize buckling, maintain alignment and, when needed, provide compressive stress in the weld metal. A backing bar or any portion of a fixture that might be contacted by the arc should be made of copper.

When backing bars are used, they should incorporate a groove of suitable contour to permit penetration of weld metal and to avoid the possibility of trapping gas or flux at the bottom of the weld. Grooves in backing bars for shielded metal-arc welding usually have a shallow semielliptical shape — 0.015 to 0.035 in. deep and $\frac{3}{16}$ to ¼ in. wide. Square-corner grooves are used with gas metal-arc and gas tungsten-arc welding to accommodate the backing gas; a machined passageway is connected to the gas supply, and holes $\frac{1}{16}$ in. in diameter are drilled 3 in. apart from the bottom of the groove to the passageway, so that the backing gas can flow along the weld. The gas flows out of the groove at the ends of the bar. Groove designs for backing bars are shown in Fig. 1.

Nickel alloys require about the same amount of clamping and restraint as low-carbon steel. The hold-down bars should be located close enough to the line of weld to maintain alignment and to provide the proper degree of heat transfer. Generally, hold-down pressure should be just enough to maintain alignment, but in welding square-groove joints in thin metal by the gas tungsten-arc process without a filler metal, high restraint can be used to advantage. When the pieces to be welded are positioned with a zero root opening, and the hold-down bars are brought very close to the line of weld-

ing and a high hold-down pressure is used, an expansive force is created by the heat of welding that will result in a compressive force in the line of weld. This compression will have an upsetting effect on the hot weld metal, and the weld will develop a slight top and bottom crown, or weld reinforcement, without the use of filler metal.

Welding of Precipitation-Hardenable Alloys

The precipitation-hardenable alloys require special welding procedures because of their susceptibility to cracking. Cracks can occur in the base-metal heat-affected zone on aging or in service at temperatures above the aging temperature, as a result of residual welding stress and stress induced by precipitation.

Preweld and Postweld Treatments. Any part that has been subjected to severe bending, drawing or other forming operation should be annealed before welding. If possible, heating should be done in a controlled-atmosphere furnace, to limit oxidation and minimize subsequent surface cleaning.

The aluminum-titanium-hardened alloys must be stress relieved (solution treated) after welding and before precipitation hardening. To avoid prolonged exposure of the welded structure to temperatures within the precipitation-hardening range, a rapid heating in a furnace preheated to the appropriate temperature is recommended. When the workpiece is large in comparison with the furnace area, it may be necessary to preheat the furnace 200 to 500 F above the solution-treatment temperature and then to reset the furnace controls when the workpiece has reached the solution-treatment temperature. The stresses created by repair or alteration welding must be relieved in a similar fashion — by rapid heating to the solution-treating temperature prior to re-aging. When it is not feasible, particularly if the structure is complicated, to stress relieve the weldment satisfactorily, preweld treatments may be helpful, but preheating is not a satisfactory substitute for postweld heat treatment.

Precipitation-hardenable alloys can be welded in the aged condition, but if temperatures encountered in service are in the precipitation-hardening range, the weldment must be solution treated and re-aged.

General Welding Procedures. Precipitation-hardenable alloys are usually welded by the gas tungsten-arc process, but shielded metal-arc and gas metal-arc welding are also applicable. Heat input during the welding operation should be held to a moderately low level to obtain the highest possible joint efficiency. For multiple-bead or multiple-layer welds, many narrow stringer beads should be used rather than a few large, heavy beads.

If oxides form during welding, they should be removed by abrasive blasting or grinding. If such films are not removed as they accumulate on multiple-pass welds, they may become thick enough to inhibit weld fusion and to produce laminar-type oxide stringers along the weld axis, which act as mechanical stress raisers, and may cause stress-corrosion cracking in service.

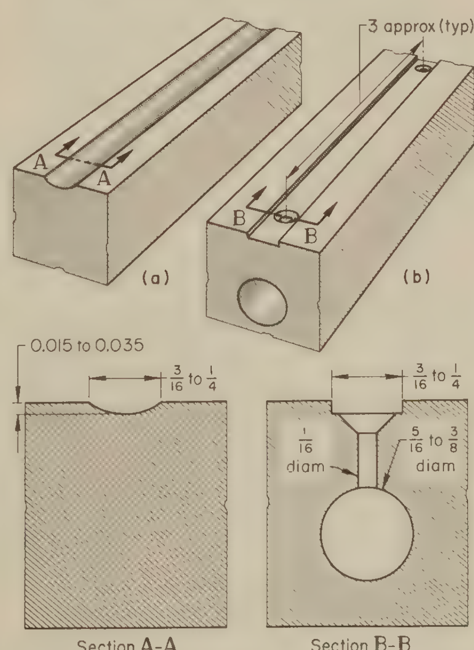
Table 1. Nominal Compositions of Weldable Wrought Nickel and Nickel Alloys

Alloy	Composition
Nickel and Solid-Solution Alloys	
Nickel 200	99.5 Ni, 0.06 C, 0.25 Mn, 0.15 Fe
Nickel 201	99.5 Ni, 0.01 C, 0.20 Mn, 0.15 Fe
Nickel 205	99.5 Ni, 0.06 C, 0.20 Mn, 0.10 Fe, 0.04 Mg
Nickel 211	95.0 Ni, 0.10 C, 4.75 Mn, 0.05 Fe
Nickel 220	99.5 Ni, 0.06 C, 0.12 Mn, 0.05 Fe, 0.04 Mg
Nickel 230	99.5 Ni, 0.09 C, 0.10 Mn, 0.05 Fe, 0.06 Mg
Nickel 233	99.5 Ni, 0.09 C, 0.18 Mn, 0.05 Fe, 0.07 Mg
Nickel 270	99.98 Ni, 0.01 C
Monel 400	66.0 Ni, 31.5 Cu, 0.90 Mn, 1.35 Fe
Monel 401	44.5 Ni, 53.0 Cu, 1.70 Mn, 0.20 Fe, 0.50 Co
Monel 404	55.0 Ni, 44.0 Cu
Monel R-405	66.0 Ni, 31.5 Cu, 1.35 Fe
Precipitation-Hardenable Alloys	
Monel K-500	65.0 Ni, 29.50 Cu, 0.60 Mn, 1.00 Fe, 0.60 Ti, 2.73 Al
Monel 502	66.5 Ni, 28.0 Cu, 0.75 Mn, 1.0 Fe, 0.25 Ti, 3.0 Al
Special-Purpose Alloys Cited in Examples in This Article	
4-79 Moly-Permalloy	79 Ni, 4 Mo, rem Fe
Mumetal (AMS 7701)	80 Ni, 15 Fe, rem Cu, Mo or Cr
Nichrome	57 Ni, 16 Cr, 27 Fe
Invar 36	35.5 Ni, 0.18 C, 0.42 Mn, rem Fe

Welding of Cast Nickel Alloys

Cast nickel alloys can be joined by gas tungsten-arc, gas metal-arc, and shielded metal-arc welding. For optimum results, castings should be solution annealed before welding, to relieve some of the casting stresses and to provide some homogenization of the cast structure.

Preheating to 200 to 400 F, depending on casting mass at the joint, reduces cracking of weld metal from thermal shock. Light peening of solidified metal after the first pass will relieve stresses and thus reduce cracking at the junction of the weld metal and the cast metal. Peening of subsequent passes is of little if any benefit. Stress relieving after welding is also desirable.



(a) Standard groove for use without a backing gas; (b) square-corner groove employed with backing gas (groove depth depends on gas flow required and length of bar)

Fig. 1. Groove designs for backing bars

Gas Tungsten-Arc Welding

Nickel alloys, both cast and wrought, either solid-solution-strengthened or precipitation-hardenable, can be welded by the gas tungsten-arc process. The addition of filler metal is usually recommended.

Straight-polarity direct current (dcsp) is recommended for both manual and machine welding. If close control of arc length is feasible, alternating current can be used for machine welding, but a superimposed high-frequency current is required.

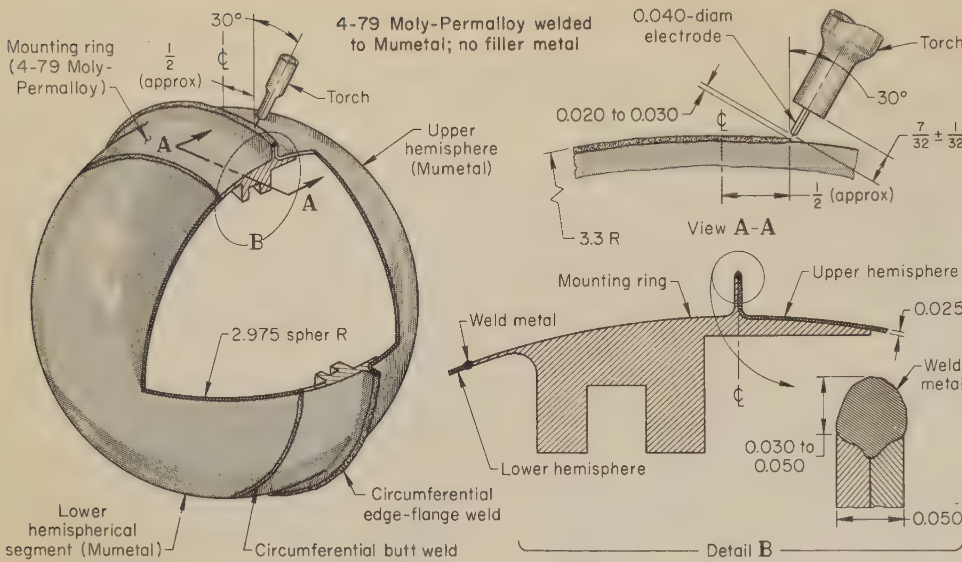
The welding torch should be set or held at an angle of 90° to the work; a slight deviation is permissible to provide a better view of the work. An acute angle can lead to pulling in of the surrounding air and contamination of the shielding gas. The largest gas-nozzle size applicable to the job should be used, and a minimum practical distance between the nozzle and the work should be maintained. A gas lens is sometimes used to control gas flow, as in Example 352.

For details of the process and equipment, see the article "Gas Tungsten-Arc Welding", beginning on page 113. Conditions for gas tungsten-arc welding of Monel 400 are given in Table 2.

Shielding Gas. Either argon or helium, or a mixture of the two, is used as a shielding gas for welding nickel and nickel alloys. Additions of oxygen, carbon dioxide, or nitrogen to argon gas will usually cause porosity, or erosion of the electrode. Argon with small quantities of hydrogen (approximately 5%) can be used for single-pass weld-

Table 2. Conditions for Manual Gas Tungsten-Arc Welding of 0.062-In.-Thick Monel 400

Joint type	Beveled butt, 1/16-in. root opening
Electrode	3/32-in.-diam EWTh-2, tapered to 1/64-in. diameter
Filler metal	1/16-in.-diam Monel 60 (ERNiCu-7)
Number of passes	Three
Welding current	70 to 90 amp, dcsp
Voltage	10 to 12 v
Shielding gas:	
At torch	20 cfh
Backing gas	3 to 5 cfh
Welding speed	2 to 3 ipm
Preheat and postheat	None
Interpass temperature	350 F max



Conditions for Automatic Gas Tungsten-Arc Welding

Weld type	Edge-flange	Power supply	320-amp transformer-rectifier with slope control; high-frequency unit
Filler metal	None	Torch	Light duty, air cooled, with gas lens
Electrode	0.040-in.-diam EWTh-2	Auxiliary equipmt	Positioner; sequence timer
Shielding gas, torch	Argon, at 45 cfh	Welding speed	18.8 ipm
Backing gas	Helium (purge)		

Fig. 2. Gyroscope instrument enclosure that was welded by the gas tungsten-arc process, and details of the edge-flange weld and torch position (Example 352)

ing, and may help to avoid porosity in pure nickel. Helium has shown the following advantages over argon in welding thin metal without the addition of filler metal:

1 **Improved Soundness.** Porosity-free welds are more easily obtained in Monel 400, and there is less porosity in welds in Nickel 200.
2 **Increased Welding Speed.** With straight-polarity direct current, welding speed can be increased as much as 40% over that achieved with argon at the same current setting, because welding speed is a function of heat input, and heat input is considerably greater with helium.

Because purity and dryness of the welding gas are important, welding-grade shielding gas should be used.

Disruption of the shielding atmosphere and drawing in of air can cause porosity in the weld metal. The welding area should be screened to avoid drafts.

Electrodes. Pure tungsten electrodes or tungsten alloyed with thorium or zirconium can be used. The alloyed electrodes are more economical because of their lower operating temperature and lower vaporization loss. Overheating through use of excessive amperage must always be avoided.

The best arc stability and penetration control are achieved by tapering the electrode tip. The taper angle should be approximately 30°, with a flat land of about 0.015-in. diameter on the tip end. Larger taper angles are used to produce a narrower bead and deeper penetration.

Electrode extension (stickout) should be short, and based on joint design. For example, a maximum extension of 3/16 in. is used for butt welds in thin metal, but a 3/8 to 1/2-in. extension may be required for some fillet welds.

The electrode should be inclined slightly in the forehand position. When filler metal is used, it should be added carefully at the leading edge of the weld puddle to avoid contact with, and contamination of, the electrode. If contamination should occur, the electrode should be cleaned and reshaped.

Filler Metals. Compositions of the filler metals used with gas tungsten-arc welding are, in general, similar to those of base metals with which they are employed. Because of high arc currents and high welding temperatures, filler metals are alloyed to resist porosity and hot cracking of the weld metal. Filler-metal additions and dilution ratios should be adjusted to ensure that the weld metal contains at least 50% filler metal.

Table 3 lists the compositions of filler metals used for gas tungsten-arc welding of nickel and nickel alloys.

Filler metals of the ERNi-3 classification are used for welding the high-nickel alloys, such as Nickel 200 and 201, and those of the ERNiCu-7 classification are used for welding nickel-copper alloys, such as Monel 400 and 404.

Filler metals ERNiCu-8 are used for welding nickel-copper-aluminum alloys, such as Monel K-500. The weld metal will age harden if heated to 1100 F and held for 16 hr, followed by furnace or air cooling. The weldment should be stress relieved before aging; if not, cracking may result during aging.

Joint Design. All of the joint designs shown in Table 3 of the article on Arc Welding of Heat-Resisting Alloys can be used in welding nickel alloys by the gas tungsten-arc process. Where no filler metal is used, the sections to be joined must be held tightly together to promote satisfactory fusion.

Welding Techniques. When a filler metal is used, the wire diameter should be related to the work-metal thickness. During welding, the hot end of the wire must be kept under the shielding gas. The molten puddle must be kept as quiet as possible; otherwise the deoxidizing elements will burn out.

To ensure a sound weld, the arc should be maintained at the shortest possible length. When no filler metal is added, the arc length should be 0.05 in. max and preferably 0.02 to 0.03 in. When filler metal is used, the arc can be longer, but it should be kept as short as possible, consistent with filler-metal diameter.

Speed of welding affects penetration and width of weld and weld soundness, especially when no filler metal is added. For a given thickness of metal, there is a range of welding speeds that results in minimum porosity. Speeds outside this range, either faster or slower, result in increased porosity. Also, for a given welding speed, the likelihood of porosity decreases as metal thickness increases.

Complete-penetration welds call for the use of grooved backing bars that permit local gas shielding such as that shown in Fig. 1(b), or the purging of the inside of the workpiece.

Production Examples. The two examples that follow describe an application of gas tungsten-arc welding in which overheating and undue stressing had to be prevented, and one in which the presence of a flux was undesirable because it might cause corrosion.

Example 352. Hermetic Sealing of 0.025-In.-Thick Mumetal to 4-79 Moly-Permalloy (Fig. 2)

The gyroscope assembly shown in Fig. 2 consisted of two hemispheres, approximately 6 in. in diameter and 0.025 in. thick, joined at the equator. A 4-79 Moly-Permalloy ring, which provided internal support for the gyro mechanism, was welded to a Mumetal hemispherical segment to form one hemisphere. The other was of Mumetal. All joints, including several connections not shown, had to provide hermetic sealing, with leak rates not to exceed 1×10^{-6} cu cm per second under internal helium pressure. Gas tungsten-arc welding was used because it could meet the precision and joint-reliability requirements.

The edge-flange weld (shown in Fig. 2) was most critical, because of the two-stage fabricating sequence. First, the outer envelope was completely assembled and welded at all joints, without the gyro mechanism. The welds were then leak tested and, after all necessary repairs had been made, the edge-flange weld was milled off so that the upper hemisphere could be removed. Then the gyro was mounted in the Permalloy equator ring, and the upper hemisphere was replaced and rewelded to seal the assembly. Considerable care was taken in rewelding the edge flange because any repair after final leak testing was highly undesirable.

Several techniques were used to obtain a smoothly contoured weld with controlled

Table 3. Compositions of Filler Metals or Electrode Wires for Gas Tungsten-Arc, Gas Metal-Arc, and Submerged-Arc Welding of Nickel Alloys(a)

AWS classification	C	Mn	Fe	S	Si	Cu	Ni + Co(b)	Al	Ti	Other, total
ERNi-3	0.15	1.0	1.0	0.01	0.75	0.25	93 min	1.5	2.0 to 3.5	0.50
ERNiCu-7	0.15	4.0	2.5	0.02	1.25	Rem	62 to 69	1.25	1.5 to 3.0	0.50
ERNiCu-8	0.25	1.5	2.0	0.01	1.0	Rem	63 to 70	2 to 4	0.25 to 1.00	0.50

(a) Values are maximum except where ranges are shown. (b) Cobalt, if determined, 1% max.

penetration, at a speed sufficient to minimize heat input to the ring. To avoid erratic arc action and porosity, all joint surfaces were required to be chemically clean. Straight-polarity direct current was used with external argon shielding to obtain good penetration. Use of a 0.040-in.-diam thoriated tungsten electrode provided high current density at relatively low current to minimize heat input. A purging flow of helium provided internal backing. The power supply incorporated sequenced arc-current and gas-flow control for starting and stopping welding. Superimposed high-frequency current provided arc stability.

A light-duty air-cooled welding torch, with a lens-type gas nozzle to reduce turbulence, was carefully positioned over the joint (Fig. 2). The torch position enabled arc force to work against gravity on the molten weld puddle to obtain a crown on the weld bead. To assist in maintaining the desired weld-bead contour, the distance of the torch from the vertical centerline (shown as approximately ½ in. in Fig. 2) was varied during welding. No filler metal was used. The entire assembly was fixtured on a special positioner that rotated at about 1 rpm. Except for the torch adjustments described above, the operation was automatically sequenced. Details of conditions and equipment used in automatic gas tungsten-arc welding are summarized in the table that accompanies Fig. 2.

The 4-79 Moly-Permalloy ring had been made by rolling a rectangular bar into a ring, flash welding the joint, and then machining the required contour. After machining, the ring was annealed at a high temperature to obtain optimum electrical properties.

Example 353. Gas Tungsten-Arc Welding of Nichrome Wire to a Nickel Tab (Fig. 3)

Originally, resistance spot welding was chosen for welding a long Nichrome (57Ni-16Cr-27Fe) lead wire to a nickel (99 Ni) tab (Fig. 3), because it was necessary to avoid the use of a flux (which might cause corrosion), but flexing at the joint caused early failure of the connection and an alternative joining method was sought. Gas tungsten-arc welding, in addition to resistance spot welding, improved the reliability of the joint. No change in workpiece design was necessary. The wire was resistance spot welded to the tab for location, and the workpiece was positioned in a welding vise (electrically grounded) and was manually gas tungsten-arc welded, without filler metal, using an air-cooled torch, a 0.040-in.-diam EWTh-2 electrode, and argon shielding gas at 18 cu ft per hour. Welding was done with 70-amp straight-polarity direct current. To facilitate arc starting and to avoid tungsten inclusions in the weld, high-frequency current was added to the welding circuit. Production rate was 30 welded connections per hour.

Nichrome (57Ni, 16Cr, 27Fe) welded to nickel (99%); no filler metal

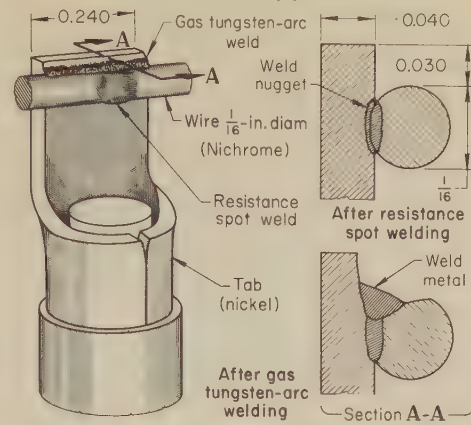


Fig. 3. Electrical connection that was gas tungsten-arc welded for high reliability (Example 353)

Welding Current. All standard direct-current power supplies have been found satisfactory, but constant-voltage power supplies are most widely used. The direct current should have reverse polarity. Deposition rates are higher with straight polarity, but weld spatter is excessive. Amperage should be well within the maximum rating of the equipment, but sufficient to obtain the desired melting rate.

Shielding Gas. For gas metal-arc welding of nickel alloys by spray or globular transfer, good results are obtained with argon as the shielding gas. The addition of 15 to 20% helium is beneficial when welding nickel alloys. The weld beads become progressively wider and flatter, and penetration decreases, as the helium content is increased from 0 to 20%. The addition of oxygen or carbon dioxide to argon results in heavily oxidized and irregular bead surfaces. The addition of hydrogen to argon causes gross porosity in nickel alloys and weld metals. Helium by itself has been used as a shielding gas, but it creates an unsteady arc with excessive weld spatter.

Gas flow rates vary from 25 to 100 cu ft per hour, depending on joint design and welding position. A flow rate of 50 cu ft per hour is most frequently used.

The choice of gas for use with short-circuiting metal transfer is influenced by the type of equipment available. Argon, without additions, is suitable for use with equipment that has both inductance and slope control. Argon gas produces convex beads, which may cause cold lapping (lack of fusion), but it also provides a pronounced pinch effect, which can be controlled by inductance. An addition of helium is helpful when induction and slope cannot be varied. Helium imparts a wetting action, and the arc is hotter; these factors greatly decrease the possibility of cold lapping. As the percentage of helium is increased, the gas flow rate must be increased to ensure adequate protection.

The size of the gas nozzle is important when using a short-circuiting arc. For example, when using a one-to-one mixture of argon and helium at a flow rate of 40 cu ft per hour through a ⅜-in.-diam nozzle, a wire-feed rate of 250 in. per minute and a current of 110 to 120 amp are maximums when good weld quality is required. With a ⅝-in.-diam gas nozzle, the wire-feed rate can be increased to over 400 in. per minute and the current can be increased to 160 to 180 amp without affecting weld quality adversely.

An argon-helium mixture is recommended as the shielding gas with a pulsed arc. Gas flow rate should be from 25 to 45 cu ft per hour. Excessive flow rate can interfere with the arc.

Electrode wires used in gas metal-arc welding are listed in Table 3. The appropriate wire diameter depends on the method used and the thickness of the base metal. With globular or spray transfer, 0.035, 0.045 and 0.062-in.-diam wire is used. The short-circuiting arc generally requires wire 0.045 in. or less in diameter.

Joint designs recommended for the gas metal-arc processes are shown in Table 3 in the article on Arc Welding of Heat-Resisting Alloys, but for the U-groove designs, using globular or spray transfer, the root radius should be decreased by about 50% and the bevel angle should be doubled. With these types of transfer, the use of high amperage on small-diameter wire produces a high level of arc force, with the result that the arc cannot be deflected from a straight line, as it can when welding is done with covered electrodes. Because the arc must contact all areas to be fused, the joint design must provide intersection with the arc force line.

When a short-circuiting arc is used, the U-groove designs are the same as those that are employed with the other arc welding processes.

Welding Techniques. Best results are obtained when the electrode holder is positioned vertical along the centerline of the joint. Some slight inclination is permissible to allow a better view of the work, but excessive displacement can cause the surrounding atmosphere to be drawn into the shielding gas, and porous or heavily oxidized welds will result. Arc length is important; too short an arc causes spatter, and too long an arc results in loss of control and reduced penetration.

Table 4. Typical Conditions for Gas Metal-Arc Welding of Nickel 200 and Monel 400

Item	Nickel 200	Monel 400
With Spray-Type Metal Transfer(a)		
Electrode wire	ERNi-3	ERNiCu-7
Voltage, v (avg)	29 to 31	28 to 30
Current, amp (avg)	375	290
Wire feed, ipm	205	200
With Short-Circuiting Transfer(b)		
Electrode wire	ERNi-3	ERNiCu-7
Voltage, v (avg)	20 to 21	16 to 18
Current, amp (avg)	160	130 to 135
Wire feed, ipm	360	275 to 290
With Pulsed-Arc Transfer(c)		
Electrode wire	ERNi-3	ERNiCu-7
Peak voltage, v	46	40
Voltage, v (avg)	21 to 22	21 to 22
Current, amp (avg)	150	110
Wire feed, ipm	160	140

(a) Argon shielding gas at 60 cu ft per hour; flat welding position; 0.062-in.-diam electrode wire. (b) Argon-helium shielding gas at 50 cu ft per hour; vertical welding position; 0.035-in.-diam electrode wire. (c) Argon or argon-helium shielding gas at 25 to 35 cu ft per hour; vertical welding position; 0.045-in.-diam electrode wire.

Gas Metal-Arc Welding

The high-nickel and nickel-copper alloys can be joined by gas metal-arc welding and, with special procedures, so can precipitation-hardenable alloys, such as Monel K-500.

Spray, globular and short-circuiting metal transfer can be used. Varying the power input will produce the different types of metal transfer. The pulsed arc, which switches from spray to globular transfer, is also used. All of these methods are based on the use of comparatively small-diameter wire that serves as both electrode and filler metal.

Table 4 lists some typical conditions for gas metal-arc welding of Nickel 200 and Monel 400 using spray-type metal transfer, short-circuiting metal transfer, and a pulsed arc.

Cold lapping (lack of fusion) can occur with the short-circuiting arc if manipulation is faulty. The torch should be advanced at a rate that will keep the arc in contact with the base metal just ahead of the weld puddle.

The manipulation and angle used with the pulsed-arc torch are similar to those used in shielded metal-arc welding. To avoid undercutting, a slight pause should be made at the limit of the weave.

Production Example. In the following example, gas metal-arc welding was used rather than shielded metal-arc welding, because it reduced alloying and increased production.

Example 354. Use of an Expanding Fixture and Gas Metal-Arc Welding To Simplify Installation of Sleeves in a Bellows Joint (Fig. 4)

Steel piping that had been nickel plated on the inside and that ranged in diameter from 30 to 54 in. was fitted with Monel bellows joints for service in transporting uranium fluoride gas. Pipe ends at the bellows joints were formed with opposing finger stops, as shown in Fig. 4. Because excessive vibration of the piping was traced to impingement of the gas stream on the finger stops, it was decided to shield these stops by installing Monel sleeves on the inside of all joints.

Pipe sections ranging from 2 to 12 ft in length were dismantled by air carbon-arc cutting. The sections were then degreased in hot trichlorethylene vapor, rinsed in water, and wiped dry. An overhead crane was used for lowering the pipe sections into large vats for cleaning.

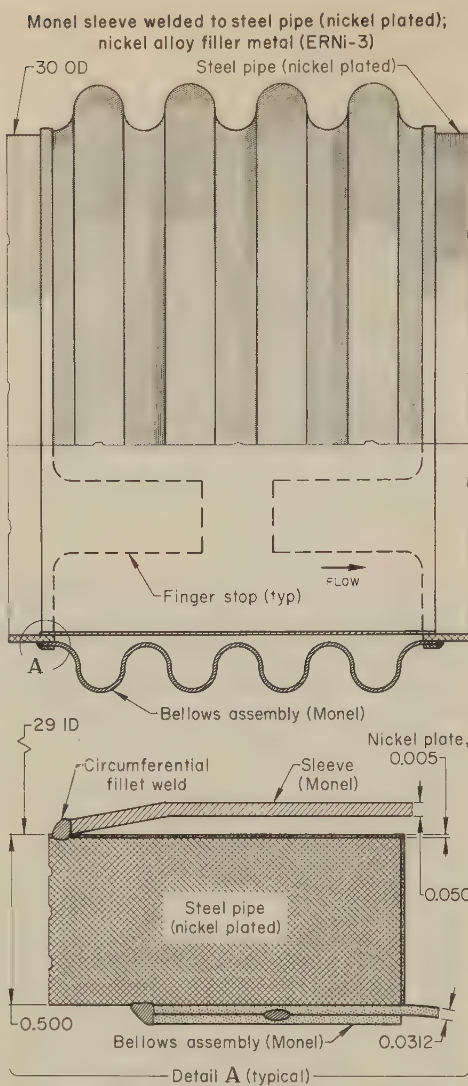
Initially the sleeves were attached in the following manner:

1 Monel sheets were rolled approximately to size with a very slight flare on the upstream side to aid in making positive contact for welding; the downstream side was left "free floating". Allowance was made on the circumference for a 1-in. overlap on the longitudinal seam.
2 The sleeves were tack welded to the pipe on the upstream side of the bellows joint, the sheet being pressed against the inside wall of the pipe by hand.
3 The sleeves were then welded to the pipe. Both tack welding and fillet welding were done by the manual shielded metal-arc process, using a ⅛-in.-diam ENiCu-4 (Monel-type) electrode at 90 amp, 30 volts. Welding speed, although not recorded, was quite low.
4 Next, the longitudinal lap joint was tacked and welded in the same manner.

This procedure was awkward and time consuming. In addition, the rather loose fit of the sleeve caused frequent melt-through, and too much alloying occurred among the nickel plating, the steel pipe, and the Monel electrode.

To improve the procedure, because a number of joints had to be repaired, the following changes were made:

1 After rolling the sheet for the sleeve approximately to size, it was fitted to the interior of the pipe and held in proper alignment for welding by means of a split ring that was expanded with a turnbuckle. This eliminated the awkward fitting and tacking operation.
2 Welding was done by the gas metal-arc process, using a bare nickel electrode wire (ERNi-3) under argon shielding. (For other welding details, see the table with Fig. 4.)



Item	Welding process: Shielded metal-arc (original)	Welding process: Gas metal-arc (improved)
Joint type	Lap	Lap
Weld type	Fillet	Fillet
Electrode	ENiCu-4	ERNi-3
Electrode size	⅛-in. diam	0.030-in. diam
Electrode holder	Standard	200 amp, air cooled
Shielding gas	None	Argon; 20-24 cfh
Welding position	Horizontal-rolled and flat	Horizontal-rolled and flat
Fixtures	None	Expandable ring and turning rolls
Current, amp	90, dcrp(a)	125 to 150, dcrp(b)
Voltage	30 v(a)	22 to 24 v(b)
Welding speed	Not recorded	18 ipm

(a) From a 400-amp constant-current rectifier. (b) From a 400-amp constant-voltage rectifier.

Fig. 4. Cutaway view of bellows joint in large-diameter nickel-plated steel pipe, showing Monel sleeve (Example 354)

Power consumption was higher with gas metal-arc welding, but welding was much faster. Joint fit-up was tighter, and so welding was simplified and took less time. Melt-through was eliminated, and alloying was reduced to a tolerable level. The original method of installing the sleeve required 16 man-hours, but the new method required only 10 man-hours. The table with Fig. 20 gives welding conditions for both methods.

Plasma-Arc Welding

Plasma-arc welding, using the keyholing mode, can produce acceptable welds in nickel alloys up to about 0.3 in. thick.

Argon-hydrogen mixtures are used as orifice and shielding gas, 5 to 8% H_2 being optimum. Current needed for keyholing decreases as hydrogen content is increased, up to about 7% H_2, above which (or when helium is used) torch starting is more difficult.

Typical relations of travel speed and current for keyhole welding are:

	Nickel 200	Monel 400
8 ipm	185 amp	155 amp
10	200	175
12	220	195
14	235	215

Typical conditions for welding 0.235-in.-thick Nickel 200, using 95% argon – 5% hydrogen gas, are: 245 amp; 31.5 v; 14 ipm; gas flow, 10 cfh (orifice) and 45 cfh (shielding). (References: A. C. Lingenfelter, *Welding Engineer*, Jan 1970, p 42-45; see also A. C. Lingenfelter and others, *Welding Journal*, May 1966, p 417-422.)

Shielded Metal-Arc Welding

The shielded metal-arc process can be used for welding nickel and nickel alloys. Although the minimum metal thickness usually is about 0.050 in., thinner metal can be welded when appropriate fixtures are provided. The types of joints used and bead and groove dimensions are given in Table 3 on page 280 in the article on Arc Welding of Heat-Resisting Alloys.

Electrodes. Compositions of electrodes used for shielded metal-arc welding are given in Table 5. Electrode composition is selected to be similar to that of the base metal with which the electrode is to be used.

Electrodes of the ENi-1 classification are used for welding wrought and cast forms of nickel and nickel alloys to themselves and to steel.

ENiCu-1 and ENiCu-2 electrodes can be used for welding nickel-copper alloys to themselves, for surfacing steel with a nickel-copper alloy, for welding the clad side of a nickel-copper clad steel, and for welding nickel-copper alloys to steel. ENiCu-2 electrodes, ³⁄₃₂ or ⅛ in. in diameter, can also be used for welding in other than the flat position. Electrodes of the ENiCu-4 classification are used for welding nickel-copper alloys to themselves for applications where the presence of columbium would decrease corrosion resistance.

ENiCuAl-1 electrodes are used for welding nickel-copper-aluminum alloys to themselves, in the unaged condition. The weld metal will respond to subsequent age hardening, but not as much as the base metal. The weldment must be stress relieved before aging, by placing it in a furnace preheated to 1450 F min, rapidly heating it to 1450 F, and holding at temperature for an appropriate length of time.

Table 5. Composition of Electrodes Used for Shielded Metal-Arc Welding of Nickel, High-Nickel Alloys, and Nickel-Copper Alloys (a)

AWS classification	C	Mn	Fe	S	Si	Cu	Ni + Co	Al	Ti	Cb + Ta	Other, total
ENi-1	0.10	0.75	0.75	0.020	1.25	0.25	92 min	1.0	1 to 4	...	0.50
ENiCu-1	0.15	4.0	2.5	0.025	1.25	Rem	62 to 70	1.0	1.5	3.0	0.50
ENiCu-2	0.15	6.0	2.5	0.025	1.5	Rem	60 to 68	1.0	1.0	2.5	0.50
ENiCu-4	0.40	4.0	2.5	0.025	1.0	Rem	62 to 70	1.5	1.0	...	0.50
ENiCuAl-1	0.45	4.0	2.5	0.025	1.25	Rem	60 to 68	1 to 4	1.0	...	0.50

(a) Single values are maximum percentages, unless otherwise noted.

Before use, covered electrodes should be kept in their sealed, moistureproof containers in a dry storage area. All opened containers of unused electrodes should be stored in a cabinet equipped with a desiccant or heated to 10 to 15 F above ambient temperature before use. If the electrodes have been exposed to excessive moisture, they can be reclaimed by rebaking.

Choice of electrode diameter should be based on quality requirements, rather than on speed of production.

Welding Current. Shielded metal-arc welding is done with reverse-polarity direct current. Each electrode size has an optimum amperage range in which it has good arcing characteristics and outside which the arc becomes unstable or the electrode overheats. Suggested electrode diameters and current settings for various metal thicknesses are shown in Table 6. Such variables as type of backing, tightness of clamping, and joint design will influence the current density needed. Actual welding currents should be developed by making sample welds in metal of the same composition and thickness as the metal to be welded.

Welding Position. Flat-position welding should be used whenever possible because it is faster and more economical and produces welds of good quality. The recommended electrode position for flat-position welding is an inclination of about 20° from the vertical, ahead of the weld puddle. This position will facilitate control of the molten flux and prevent slag entrapment. A short arc must be maintained.

For vertical welding, the arc should be slightly shorter than for flat-position welding, and the amperage should be 10 to 20% lower than the values in Table 6. The electrode should be at approximately a 90° angle to the joint.

For overhead welding, the arc should be slightly shorter than for flat-position welding, and the welding current should be reduced by 5 to 15 amp from the values shown in Table 6.

Welding Techniques. Because molten nickel alloy weld metal does not flow, it must be deposited where it is needed. Therefore, it is necessary to weave or oscillate the electrode slightly. The amount of weave will depend on joint design, welding position, and type of electrode. A straight stringer bead laid down without weaving can be used for single-pass work, and will be satisfactory at the bottom of a deep groove on thicker sections, but a weave is generally desirable.

When a weave is used, it should be no wider than about three times the electrode diameter. Some deviation from this rule may be necessary during vertical welding.

Weld spatter should be avoided. When spatter occurs, it is an indication that the arc is too long, excessive amperage is being used, or current is straight polarity.

Arc blow can occur when the arc is deflected from its normal path by a magnetic force in the work metal. One method of overcoming arc blow is to change the location of the ground connection on the workpiece to reduce the length or change the direction of the electrical path to the arc.

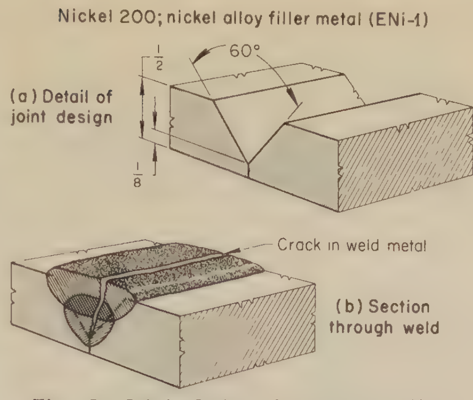
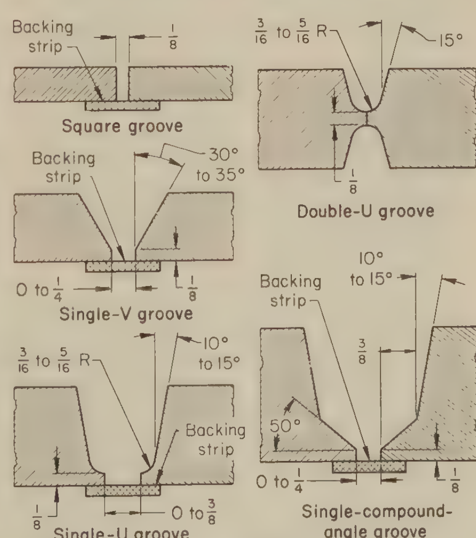


Fig. 5. Joint design for welding ½-in. Nickel 200, and crack in weld metal caused by excessive heat input

When the arc is to be broken, it should be shortened slightly and the rate of travel increased to reduce the size of the weld puddle. This practice reduces the probability of crater oxidation, ensures that the crater does not develop a rolled leading edge, and prepares the way for restriking the arc.

The manner in which the arc is restruck has a significant effect on the soundness of the weld. A reverse (or T) restrike is recommended. The arc should be struck at the leading edge of the crater and carried back to the extreme rear of the crater at a normal welding speed. The direction is then reversed, weaving is commenced, and the weld continued. This procedure has three advantages: (*a*) the welder has an opportunity to establish the correct arc length before actual welding commences; (*b*) some preheat is applied to the cold crater; and (*c*) the first drops of rapidly cooled weld metal are deposited where they will be remelted, thus keeping porosity to a minimum.

Another technique is to make the restrike where the weld metal can be readily removed — for example, ½ to 1 in. behind the crater on top of the previous pass. Later the restrike area can be ground level with the rest of the bead. This technique is used when the welds must meet rigid radiographic standards, and calls for less welder skill than the reverse-restrike method.



Backing strips are optional with zero root openings. See Table 7 for filler-metal requirements for single-compound-angle-groove, single-U-groove, and single-V-groove joints of various sizes in plate from 1 to 4 in. thick.

Fig. 6. Joint designs for submerged-arc welding of nickel alloys

Table 6. Recommended Electrode Diameter and Welding Current for Shielded Metal-Arc Welding of Various Thicknesses of High-Nickel Alloys and Nickel-Copper Alloys in the Flat Position

Base-metal thickness, in.	Electrode diameter(a), in.	Current(b), amp
High-Nickel Alloys		
0.037	3/32	(c)
0.043	3/32	(c)
0.050	3/32	(c)
0.062	3/32	75
0.078	3/32	80
0.093	3/32	85
0.109	1/8	105
0.125	1/8	105
0.125	3/32-5/32	80-150
0.140	5/32	130
0.156	5/32	135
0.187(d)	5/32	150
Nickel-Copper Alloys		
0.037	3/32	(c)
0.043	3/32	(c)
0.050	3/32	(c)
0.062	3/32	50
0.078	3/32	55
0.093	3/32	60
0.109	3/32	60
0.109	1/8	65
0.125	3/32-5/32	60-140
0.140	3/32-5/32	60-140
0.156	3/32-5/32	60-140
0.250	3/32-5/32	60-140
0.375	3/32-3/16	60-180
0.500(d)	3/32-3/16	60-180

(a) Where a range is shown, the smaller-diameter electrodes are used for the first passes at the bottom of the groove, and the joints are completed with the larger-diameter electrodes. (b) Current should be in the range recommended by the electrode manufacturer. (c) Use minimum amperage at which arc control can be maintained. (d) And thicker.

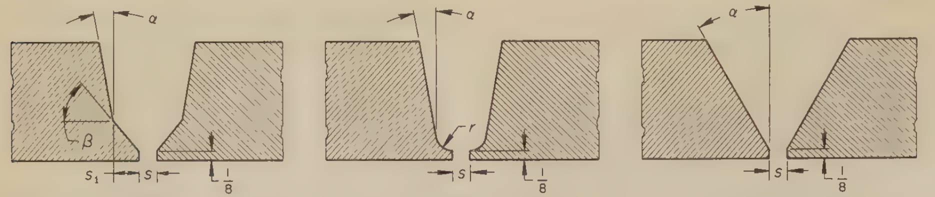
Welding procedures should be qualified, using scrap material, before production is begun. In one plant, this was not done, and when cracks appeared in the weld metal of a joint in a ½-in.-thick Nickel 200 cylinder, it was decided to run qualifying tests of the welding procedure before further welds were made.

The original procedure specified a V-groove butt joint with a 60° included angle, a ⅛-in. root face, and zero root opening, as shown in Fig. 5(a). An ENi-1 electrode that was 14 in. long by 3/16 in. in diameter was used with a welding current of 235 amp. On the first pass, a weld bead 6½ in. long was deposited with each electrode, and on the second pass, a weld bead 3 in. long was deposited with each electrode. A cross section of the completed weld is shown in Fig. 5(b). Investigation showed that cracks in the weld metal were caused by the high welding current and low filler-metal deposition rate, which had resulted in the weld puddle being held in a superheated condition for an excessively long time.

A qualified procedure was therefore established that specified a welding current of 210 amp and a filler-metal deposition rate of about 12 in. for each electrode on the first pass and 9 in. on the second pass. Electrode type and length, and all other welding conditions were unchanged.

An included angle of 80° and a 1/16 to 3/32-in. root face would have produced a

Table 7. Amount of Filler Metal Required for Submerged-Arc Welds in Three Types of Grooves



Single-compound-angle groove Single-U groove Single-V groove

Joint design: Angle α	Angle β; or radius, r	Root opening, s	Dimension s_1	Approximate amount of metal required, lb per linear foot, for plate thickness, in., of: 1	1¼	1½	1¾	2	2½	3	3½	4
Single-Compound-Angle Groove												
10°	40°	0	⅜ in.	2.19	3.10	4.10	5.17	6.33	8.90	11.77	14.95	18.50
10°	40°	0	½ in.	2.74	3.56	4.84	6.16	7.61	10.45	13.73	17.32	21.00
10°	50°	0	⅜ in.	1.95	2.83	3.79	4.82	5.93	8.40	11.18	14.00	17.70
15°	50°	0	⅜ in.	2.03	2.95	4.08	5.29	6.62	9.68	13.20	17.30	21.78
10°	50°	¼ in.	⅜ in.	2.87	3.98	5.17	6.43	7.77	10.70	13.94	17.22	21.38
10°	40°	¼ in.	⅜ in.	3.11	4.25	5.48	6.78	8.17	11.20	14.53	18.17	22.18
Single-U Groove												
10°	3/16 in.	0	...	1.46	2.07	2.76	3.53	4.37	6.33	8.60	11.20	14.10
10°	¼ in.	0	...	1.77	2.47	3.25	4.12	5.06	7.20	9.67	12.45	15.60
10°	5/16 in.	0	...	2.03	2.86	3.68	4.71	5.76	8.10	10.70	13.70	17.00
15°	3/16 in.	0	...	1.60	2.36	3.23	4.22	5.34	7.94	11.00	14.60	18.68
15°	¼ in.	0	...	1.90	2.73	3.68	4.76	5.96	8.74	12.00	15.78	20.00
15°	5/16 in.	0	...	2.17	3.08	4.14	5.30	6.60	9.55	12.90	16.90	21.40
10°	3/16 in.	¼ in.	...	2.38	3.22	4.14	5.14	6.21	8.63	11.36	14.42	17.78
10°	¼ in.	¼ in.	...	2.69	3.62	4.63	5.73	6.90	9.50	12.43	15.67	19.28
Single-V Groove												
30°	...	0	...	1.63	...	...	...	...	...	...	...	...
35°	...	0	...	1.96	...	...	...	...	...	...	...	...
30°	...	¼ in.	...	2.55	...	...	...	...	...	...	...	...

better welded joint, but the workpieces had been machined and roll formed before the problem arose.

Cleaning the Weld Bead. In multiple-pass welding, all flux and slag must be removed before each succeeding bead is deposited. All slag should be completely removed from completed welds, especially if service is to be at high temperature. The slag is easily removed with hand tools or a hand or power wire brush.

Submerged-Arc Welding

Submerged-arc welding can be used for joining solid-solution nickel alloys, Monel 400 being the alloy most commonly welded by this process. Joints in metal up to 3 in. thick have met ASME codes and other specification requirements. The submerged-arc process cannot be used for welding the precipitation-hardenable nickel alloys.

Joint Design. Some joint designs used in the submerged-arc welding of nickel alloy plate are shown in Fig. 6. Single-compound-angle grooves, single-U grooves, and double-U grooves are used for metal ¾ in. or more thick. The double-U groove is usually preferred. It results in a lower level of residual stress, and it can be completed in less time and with less filler metal. A single-V groove is used for stock up to 1 in. thick.

Electrodes. The compositions of the electrode wires used in submerged-arc welding are the same as the filler metal or electrode wires used for gas tungsten-arc and gas metal-arc welding (see Table 3). Electrode ERNiCu-7, with a suitable flux, is suggested for welding Monel 400.

Wire ranging from 0.045 to 3/32 in. in diameter can be used for all nickel alloys. The 1/16-in.-diam wire is generally preferred. Small-diameter wires are used for welding metal up to ½ in. thick, and 3/32-in.-diam wires for heavier sections.

The approximate amount of filler metal needed for single-compound-angle, single-U and single-V grooves is given in Table 7.

Fluxes used in submerged-arc welding of carbon and stainless steels are not satisfactory for welding nickel alloys. Special proprietary fluxes are available and must be used. Poor weld contour, flux entrapment, weld cracking, and inclusions can result when the wrong flux is used.

Only enough flux cover to prevent arc breakthrough should be used — excessive flux can cause a deformed bead surface. Slag entrapment can be prevented by use of an appropriate joint design and by correct placement of beads. Slag is easily removed from welds in the bottom of grooves. Fused flux is self-lifting from exposed welds and should be discarded. Unfused flux can be recovered by means of a vacuum system and, if clean, it can be reused. Screening to adjust particle size is not required.

Fluxes should be stored in dry storage areas. Opened containers should be resealed to prevent moisture pickup, but flux that has absorbed moisture can be reclaimed by drying at 600 F for 1 hr. Hoppers used for fluxes for welding steel and other metals should be thoroughly cleaned before being filled with flux for welding nickel alloys.

Welding Current. Direct current with either straight or reverse polarity is used. Reverse polarity is preferred for butt welding because it produces a flatter bead with deeper penetration, at a rather low arc voltage (30 to 33 volts). Straight polarity will result in a slightly higher rate of deposition at increased voltage (over 35 volts), but the flux covering must be appreciably deeper, and there will be a consequent increase in flux consumption and a greater risk of slag entrapment.

Alternating current and the two-wire series technique for multiple-arc welding are not suited to use with the available fluxes.

Bead Deposition. Location of a bead in a multiple-pass layer should be such as to provide an open, or reasonably wide, root area for the next bead. Flat or slightly convex beads are preferred to concave beads. Bead contour is controlled by voltage, travel speed, and the position of the electrode.

Production Example. The following example describes submerged-arc welding of an iron-nickel alloy. The application is unique. Submerged-arc welding produced satisfactory results.

Example 355. Submerged-Arc Welding Technique for Fabricating a Large Pressure Vessel From Invar 36 (Fig. 7)

Invar 36, because of its dimensional stability, was used to make a cylinder that was 48 ft long by 10 ft in diameter, with a ¾-in. wall. This large cylinder was made by welding together eight 6-ft-long cylinders. Each 6-ft cylinder had to be welded longitudinally, as shown in Fig. 7.

Because Invar 36 is not generally used in structures of this size, welding procedures had not been developed. Gas tungsten-arc welding was the only process that had been qualified for welding Invar 36, but use of this process would have been expensive for eight 6-ft-long welds and the possible use of a faster process was explored, using 5-by-10-in. test plates.

Gas metal-arc welding was tried first, but radiographic inspection showed porosity in the welds, and the process was rejected. Next, submerged-arc welding was tried, using practices developed for welding nickel-copper alloys; this process produced satisfactory welds on the test plates (see Fig. 7) and was used for the production welds. The conditions finally adopted for submerged-arc welding of the Invar 36 cylinders are given in the table with Fig. 7.

A V-groove, as shown in Fig. 7, was machined on the inside of the joint, and the cylinder was tack welded and set on turning rolls so that welds on the inside and outside could be made in the flat position. A root pass was made without preheating, the work was allowed to cool to 200 F max, and a second pass completed the weld on the inside of the cylinder.

The outside of the joint was arc-air gouged to sound weld metal and then ground, leaving a smooth U-groove. The outside of the joint was then welded in nine passes. The work was cooled to 200 F max between passes. The electrode extension of ⅞ ± ⅛ in. allowed close control of metal deposition and was adequate for the flux cover.

The time for making a longitudinal weld by submerged-arc welding was approximately 25% of that estimated for making the weld by gas tungsten-arc welding, and the estimated cost saving was 75%.

Causes and Prevention of Weld Defects

The defects and metallurgical difficulties encountered in arc welding of nickel alloys are porosity, susceptibility to high-temperature embrittlement by sulfur and other contaminants, cracking in the weld bead because of high heat input, and stress-corrosion cracking in service.

Porosity in welds can be caused by oxygen, carbon dioxide, nitrogen or hydrogen. In shielded metal-arc and

submerged-arc welding, porosity can be minimized by using electrodes that contain deoxidizing or nitride-forming elements such as aluminum and titanium, which have a strong affinity for oxygen and nitrogen and form stable compounds with them.

In gas metal-arc and gas tungsten-arc welding, porosity can be avoided by preventing access of air to the molten weld metal. Gas backing on the underside of the weld is sometimes used.

In gas tungsten-arc welding, the use of argon with up to 20% hydrogen as a shielding gas will help to prevent porosity. The hydrogen acts as a scavenger, the nitrogen diffusing into the bubbles of hydrogen that form in the weld puddle. Too much hydrogen in the shielding gas can result in hydrogen porosity.

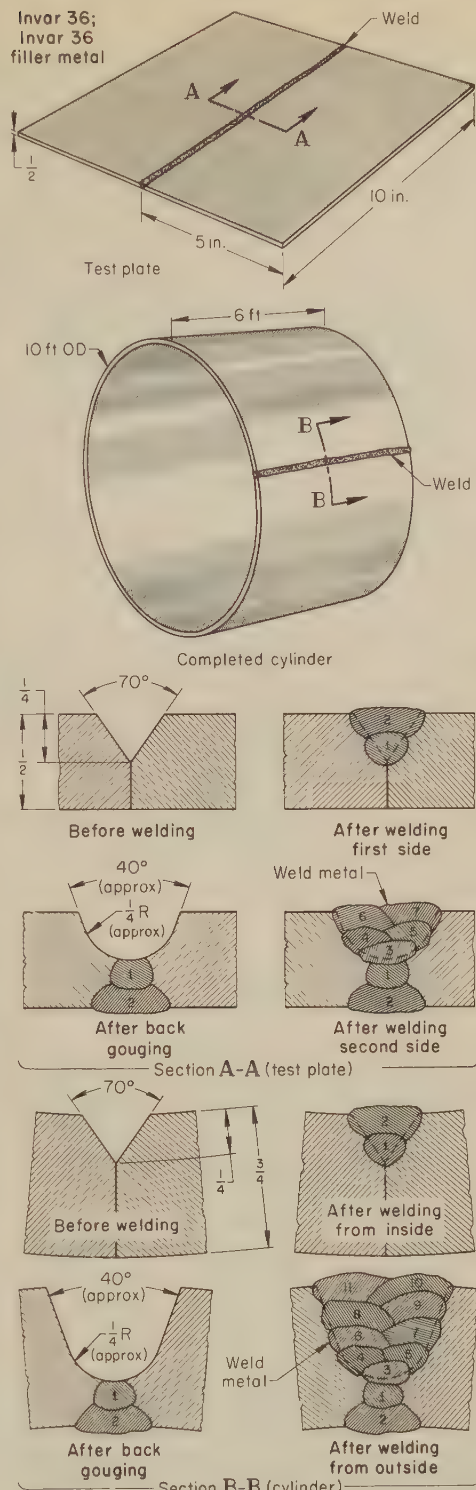
Cracking. Hot shortness of welds can result from contamination by sulfur, lead, phosphorus, or low-melting-point metals such as bismuth, which form intergranular films that cause severe embrittlement at elevated temperature. Hot cracking of the weld metal usually results from such contamination. Cracking in the heat-affected zone is often caused by intergranular penetration of contaminants from the base-metal surface. Sulfur, which is present in most cutting oils used for machining, is a common cause of cracking in nickel alloys. Removal of foreign material from the surfaces of the work metal is imperative, and is described on page 366.

Cracking of the weld metal also can be caused by too high heat input as a result of high welding current and low welding speed (Fig. 5). Cracking can also be caused by undue restraint.

Stress-Corrosion Cracking. Nickel and nickel alloys generally do not undergo any metallurgical changes, either in the weld metal or in the heat-affected zone, that affect normal corrosion resistance, but when the alloys are to be used in contact with substances such as concentrated caustic soda, fluosilicates and some mercury salts, the welds may need to be stress relieved to avoid stress-corrosion cracking. Nickel alloys have good resistance to dilute alkali and chloride solutions. Resistance to stress-corrosion cracking increases with nickel content, and so stress relieving of welds in high-nickel alloys is not usually needed.

Effect of Slag on Weld Metal. The slag formed on the weld surface by covered electrodes is not normally detrimental to the service life of weldments. Slag inclusions between weld beads reduce the strength of the weld. If the service temperature approximates the melting point of the slag, severe corrosion can occur if slag is present on the weld surfaces, particularly in oxygen-containing atmospheres.

Slag also acts as an accumulator of sulfur, particularly in reducing atmospheres, and this can lead to service failure in atmospheres that would be considered adequately low in sulfur. For example, in one instance, although only 0.01% sulfur was present in the atmosphere, the sulfur content of the slag on the weld surface rose from 0.02% to 2 or 3% after a one-month exposure. Sulfur pickup also depresses the melting temperature of the weld slag, and consequently the maximum safe operating temperature of the weldment.



Conditions for Submerged-Arc Welding

Joint type	Butt
Weld type	V-groove and U-groove
Joint preparation	Machining
Electrode	1/16-in.-diam Invar 36 wire
Electrode holder	Semiautomatic, 500 amp
Electrode extension	7/8 ± 1/8 in.
Flux	Proprietary Monel welding flux
Welding position	Flat
Number of passes	11
Interpass temperature	200 F max
Power supply	500-amp constant-voltage welding machine, with wire feeder
Current	280 to 300 amp, dcrp
Voltage	34 v
Welding speed	10 to 15 ipm

Fig. 7. Cylinder made of Invar 36 by submerged-arc welding, as shown (Example 355)

Joining of Dissimilar Metals

Nickel and nickel alloys have been successfully joined to other nickel alloys, to low-carbon steel, stainless steel, and copper alloy 260 (cartridge brass). Filler metal, or consumable electrode, must be selected so as to ensure a compatible metallurgical relationship between the two base metals. Several factors are involved: differences in thermal expansion of the base metals, the possibility of permanent changes in volume after extended service at elevated temperature, and the effect of weld-metal dilution at the interfaces with the base metal. All of these factors influence the choice of filler metal and welding process.

An example of a good metallurgical combination is the welding of nickel to Monel. Because these metals are completely compatible, they can be welded to each other by any welding process, using any compatible filler metal, without difficulty.

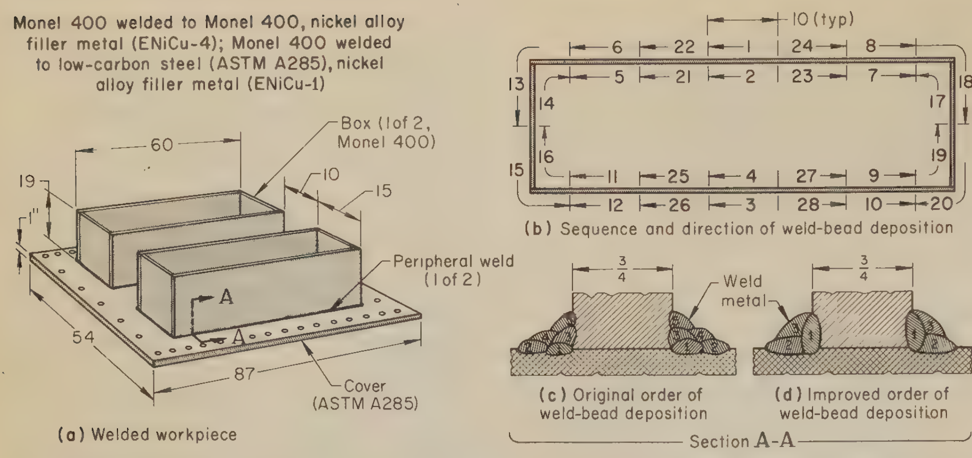
Dilution of Weld Metal. The composition of the weld metal can be expected to differ from that of the filler metal or consumable electrode, or the base metals being joined, because some elements are transferred from the base metal to the weld metal during welding. This mixing results in the formation of another alloy. The composition of the weld metal is fairly uniform for a given bead, except in a narrow band at the edge of the joint. The amount of dilution will vary from bead to bead. The welding process, current density, welding speed, work-metal thickness, and welding technique influence the amount of dilution.

The dilution of a nickel-base alloy by a dissimilar metal can be tolerated only to a limited degree. In welding Monel to an austenitic stainless steel, if a stainless steel filler metal is used, any significant amount of copper pickup from the Monel will cause the weld metal to become hot short and to crack. Thus, stainless steel filler metal should not be used when the welding process can cause a considerable amount of dilution. A Monel filler metal cannot be used in this instance because chromium from the stainless steel will dilute the weld metal and cause cracking. A nickel or an Inconel filler metal is best, but either should by used only after the welding procedure has been qualified by tests.

Filler metal must be selected so that the resultant weld will meet the service requirements for strength, corrosion resistance, and soundness, and so that dilution can occur without causing susceptibility to cracking in the weld metal. Crack sensitivity of the weld metal is proportional to the amount of dilution, especially where there is considerable difference in the compositions of a base metal and a filler metal.

Some combinations of base metal and filler metal produce undesirable weld-metal compositions, for example:

1 A ferritic weld-metal deposit diluted by nickel, chromium or copper
2 An 18-8 stainless steel weld-metal de-



Item	Original method	Improved method
Type of joint and weld:		
Monel 400 to Monel 400 ...	Corner, double fillet	Corner, double fillet
Monel 400 to steel	T, double fillet	T, double fillet
Welding passes:		
Monel 400 to Monel 400 ...	One	One
Monel 400 to steel	Five	Three
Fixtures	None	Clamps
Electrode:		
Monel 400 to Monel 400 ...	5/32-in.-diam ENiCu-4	5/32-in.-diam ENiCu-4
Monel 400 to steel	5/32-in.-diam ENiCu-1	3/16-in.-diam ENiCu-1
Power supply	400 amp, dc	400 amp, dc
Welding current:		
Monel 400 to Monel 400 ...	130 amp, dcrp	130 amp, dcrp
Monel 400 to steel	154 amp, dcrp	145 to 150 amp, dcrp
Stress relief	1 hr at 1150 ± 25 F	1 hr at 1150 ± 25 F
Leak test(a)	Welds rejected	Welds accepted
Welding time per cover	40 hr	25 hr
Weld penetration:		
Bead 1	1/16 in. into steel	1/8 in. into Monel 400, 1/64 in. into steel
Bead 2	1/16 in. into steel	1/32 in. into steel
Bead 3	1/16 in. into Monel 400	1/32 in. into Monel 400
Bead 4	None in base metal	....
Bead 5	1/32 in. into Monel 400	....
Iron in weld metal(b):		
Bead 1	30%	7%
Bead 2	30%	10%
Bead 3	20%	4%
Beads 4 and 5	7%	....

(a) Helium mass spectrometer, internal vacuum of 0.025 mm of mercury. (b) An ENiCu-1 electrode has a nominal iron content of 2.5%.

Fig. 8. Fluorine-generator cover made by shielded metal-arc welding of Monel 400 to Monel 400 and to low-carbon steel (ASTM A285). Sequence and direction of weld-bead deposition, and order of bead deposition for original and improved welding procedures. (Example 356)

posit diluted by more than 3% copper

3 An 18-8 type of weld-metal deposit diluted by nickel or chromium sufficiently to result in the crack-sensitive weld-metal composition of 35% nickel and 15% chromium

4 A high-carbon Monel weld deposit diluted by iron

5 Any Monel weld deposit diluted by more than 6 to 8% chromium.

Manipulation of the welding arc so that it impinges mainly on the base metal nearest in composition to the filler metal, as in Example 356, will help reduce dilution. For most combinations of dissimilar metals, suppliers of filler metal should be consulted before a filler metal is selected.

The coefficients of thermal expansion of the base metals must be considered in selecting filler metal for joining dissimilar-metal combinations. A large difference in expansion can induce stresses of sufficient magnitude to produce cracking in the weld metal. Some of the Inconel (ENiCr, ENiCrFe, ERNiCr and ERNiCrFe) electrodes and filler metals can be used for welding a wide range of base-metal combinations. These electrodes and filler metals can tolerate considerable dilution without loss of strength or ductility.

Filler metal ERNiMo-6 (Hastelloy W) can be used for joining nickel-base alloys, cobalt-base alloys, and stainless steels to themselves and to other metals and alloys.

Welding Processes. Gas tungsten-arc welding can be used to join dissimilar combinations of nickel alloys. When joining dissimilar metals by the gas metal-arc process, the spray or pulsed-arc mode of metal transfer should be used.

Shielded metal-arc welding is widely used for joining nickel alloys to dissimilar metals. The welding current should be maintained near the middle of the recommended range for the electrode, to control dilution. Dilution usually can be kept below 25% by manipulating the electrode so that the arc force is dissipated on weld metal already deposited. When depositing the first bead, the arc should be directed toward the member from which dilution of the weld metal will be least detrimental. Welding procedures that reduce the amount of penetration (which can cause dilution of the weld metal by the base metal) increase the probability of securing a good weld.

In the following example, Monel 400 plates were welded to a low-carbon steel plate. Cracks resulting from excessive dilution were eliminated by modifying the way in which the beads were deposited, and weld crater cracks were prevented by care in ending the weld bead and in breaking the arc.

Example 356. Elimination of Cracking of Welds and Distortion of Base Plate in Joining Monel 400 to Steel (Fig. 8)

Welding of a Monel 400 skirt box to a low-carbon steel (ASTM A285) cover for a fluorine generator resulted in cracking of the weld metal and warping of the cover. The Monel 400 skirt boxes replaced low-carbon steel skirt boxes that had corroded.

The original procedure for removing corroded skirt boxes, making new boxes, and welding the new boxes to the cover plate was as follows:

1 Remove corroded low-carbon steel skirt boxes by air carbon-arc cutting.
2 Clean surfaces of low-carbon steel cover by surface grinding.
3 Clean all joint areas on the Monel 400 plates with trichlorethylene, and remove mill scale with a surface grinder.
4 Assemble Monel 400 skirt box and weld the four corners in one pass each with a 5/32-in.-diam ENiCu-4 (Monel 130) electrode, using a welding current of 130 amp.
5 Weld the Monel 400 skirt box to the low-carbon steel cover with intermittent welds, using the sequence of weld-bead deposition shown in Fig. 8(b). (The box and cover were first tack welded at the starting place for each of the 10-in.-long welds.) Deposit five beads, as shown in Fig. 8(c), with a 5/32-in.-diam ENiCu-1 (Monel 140) electrode, using a welding current of 154 amp.
6 Stress relieve at 1150 ± 25 F for 1 hr in a reducing atmosphere. (The assembly was placed in the furnace when furnace temperature was less than 600 F, and after heating was allowed to cool to 600 F before it was removed.)
7 Test the welds with a helium mass spectrometer under an internal vacuum of 0.025 mm of mercury. Welds that failed the test were rewelded.

During deposition of the first bead, considerable arc blow toward the Monel 400 skirt box was encountered. The ground connection was repositioned several times, but no improvement was obtained. When the welds were tested with a helium mass spectrometer, leakage due to cracks in the weld beads was detected. Investigation revealed that some cracks had resulted from excessive dilution of the weld metal by iron (analysis showed 30% iron in bead 1 in Fig. 8c), a result of the high welding heat, and that cracks in the weld craters had been caused by ending beads too abruptly. In addition to the cracking, there was excessive distortion of the cover, the cover edges being warped upward toward the skirt boxes, 1/8 in. max along the sides and about 1/4 in. across the ends. The distortion was not reduced during stress relieving (step 6).

Experimentation resulted in the adoption of a new welding procedure (step 5) that minimized distortion and eliminated weld-metal cracking. (The remaining steps in the original procedure were retained unchanged.) In this procedure, when welding the box to the cover plate, both parts were securely clamped to a welding surface plate. The sequence of weld-bead deposition was the same as for the original method (Fig. 8b), but only three weld beads were deposited (Fig. 8d). Bead 1 was laid mostly on the Monel 400, which resulted in considerably less dilution by iron (7% compared with 30%). The bead was ended very slowly so as to avoid the danger of subsequent crater cracking. The welds were made with a slightly larger electrode than originally (3/16-in.-diam ENiCu-1 instead of 5/32-in.-diam) and using 145 to 150-amp welding current instead of 154-amp. These modifications reduced the current density and thus the heat input.

When the clamps were released, no significant distortion of the cover plate was observed, and all joints passed the helium leak-detection test. Details of the original and improved methods are given in the table that accompanies Fig. 8.

Arc Welding of Titanium and Titanium Alloys

*By the ASM Committee on Fabrication of Titanium**

TITANIUM and most titanium alloys can be welded by the gas tungsten-arc, plasma-arc, and gas metal-arc processes; procedures and equipment are generally similar to those used for welding austenitic stainless steel or aluminum. However, because titanium and titanium alloys are extremely reactive above 1000 F, more care must be taken to shield the weld and the hot root side of the joint from air than is required during the welding of austenitic stainless steel or aluminum alloys (see comparison of setups in Fig. 1).

Weldability

Unalloyed titanium and all of the alpha titanium alloys are weldable. The alpha-beta alloy Ti-6Al-4V and other weakly beta-stabilized alloys are also weldable, but strongly beta-stabilized alpha-beta alloys are embrittled by welding. Most beta alloys can be successfully welded. However, heat treatment to strengthen the weld by age hardening should be used with caution because aged welds in some beta alloys can be quite brittle.

Unalloyed titanium is generally available in several grades ranging in purity from 98.5 to 99.5% titanium. All grades usually are welded in the annealed condition, rather than in the cold worked condition.

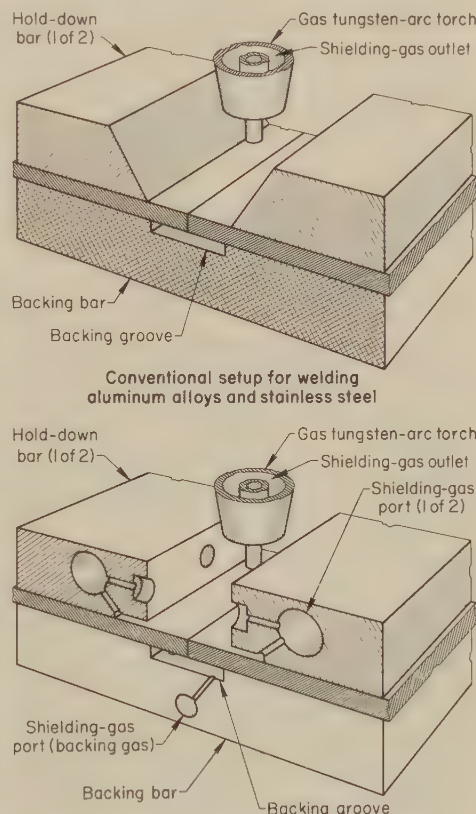
Alpha alloys Ti-5Al-2.5Sn, Ti-5Al-5Sn-5Zr, Ti-7Al-12Zr, Ti-6Al-2Cb-1Ta-1Mo and Ti-8Al-1Mo-1V are always welded in the annealed condition.

Alpha-Beta Alloys. Ti-6Al-4V can be welded in the annealed condition or in the solution-treated and partially aged condition, with aging being completed during postweld stress relieving.

In contrast to unalloyed titanium and the alpha alloys, which can be strengthened only by cold work, the alpha-beta and beta alloys can be strengthened by heat treatment.

The low weld ductility of most alpha-beta alloys is caused by phase transformations in the weld zone or in the heat-affected zone. Alpha-beta alloys have been welded with unalloyed titanium or alpha titanium alloy filler metals to lower the beta content of the fusion zone and improve weld ductility. The use of such filler metals does not prevent embrittlement of the heat-affected zone in susceptible alloys. Low-alloy welds can be embrittled by hydride precipitation.

Beta alloys Ti-3Al-13V-11Cr, Ti-4.5Sn-6Zr-11.5Mo, Ti-8Mo-8V-2Fe-3Al, and Ti-3Al-8V-6Cr-4Zr-4Mo are weldable in the annealed or heat treated condition. Welds are low in strength but ductile in the as-welded condition, and beta-alloy weldments are most often used in this condition. Welds in the Ti-3Al-13V-11Cr alloy embrittle more severely when age hardened. To obtain full strength, the beta alloys can be welded in the annealed condition, the weld cold worked by peening or planishing, and the weldment then solution treated and aged. With this procedure, adequate ductility may be obtained in the weld.



(Upper view) For welding aluminum alloys and stainless steel, gas shielding is from the torch, use of shielding gas in the backing groove being optional. *(Lower view)* For welding titanium and titanium alloys outside a welding chamber, gas shielding is from the torch and through ports in hold-down bars and backing bars.

Fig. 1. Typical setups for inert-gas shielding for gas tungsten-arc welding

Welding Processes

Gas tungsten-arc welding is the process that is most widely used for joining titanium and titanium alloys. Square-groove butt joints can be welded without filler metal in base metal up to 0.10 in. thick. For thicker base metal, the joint should be grooved and filler metal is required.

Plasma-arc welding is applicable to the welding of titanium and titanium alloys (see the article on Plasma-Arc Welding, which begins on page 138). Plasma-arc welding is faster than gas tungsten-arc welding and also can be used on thicker sections. For instance, titanium alloy plate up to ½ in. thick can be welded in one pass, using square-groove butt joints and the keyhole technique.

Gas metal-arc welding is used for joining titanium and titanium alloys more than ⅛ in. thick, and is less costly than gas tungsten-arc welding, especially when base-metal thickness is greater than ½ in. Titanium and titanium alloys are also welded by the electron beam process; this process is described in the article "Electron Beam Welding", which begins on page 519.

Filler Metals

Fourteen titanium and titanium alloy filler-metal (or electrode) classifications are given in AWS A5.16-70. Five of these are essentially unalloyed titanium and the remainder are titanium alloy filler metals.

Maximums are set on carbon, oxygen, hydrogen and nitrogen contents. The compositions of two grades of ERTi-6Al-4V filler metal are as follows:

	ERTi-6Al-4V	ERTi-6Al-4V-1
Carbon	0.05 max	0.04 max
Oxygen	0.15 max	0.10 max
Hydrogen	0.008 max	0.005 max
Nitrogen	0.020 max	0.012 max
Aluminum	5.5-6.75	5.5-6.75
Vanadium	3.5-4.5	3.5-4.5
Iron	0.25 max	0.15 max

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Ernest Dell, Vice President, Tri-D Corp.; V. V. Donaldson, Senior Applications Engineer, Edgewater Corp.; Gene F. Erbin, formerly General Manager, Technical Service and Development, Titanium Metals Corp. of America; Glenn Faulkner, (formerly with Aerojet General Corp.); Rex A. Ford, Chief, Manufacturing Research and Development, Vought Aeronautics Co., LTV Aerospace Corp.; Gerald Garfield, Principal Staff Engineer – Operations, McDonnell Douglas Astronautics Co., Western Div., McDonnell Douglas Corp.; Larry S. Klass, Staff Engineer, Aerostructures Div., Avco Corp.; W. F. Osterloh, Manufacturing Engineer, McDonnell Douglas Corp.; Gunther Pfanner, Chief, Manufacturing Research and Processes, Republic Aviation Div., Fairchild Hiller Corp.

R. M. Potter, Senior Research Engineer, Material and Process Laboratory, Columbus Div., North American Rockwell Corp.; I. J. Stewart, Research Associate, Cincinnati Milacron, Inc.; Vernon R. Thompson, Technical Director, Process Research Laboratory, Crucible Steel Co. of America; T. L. Wile, Supervisor, Machining and Fastening Group, Manufacturing Research and Development, Supersonic Transport Branch, Boeing Co.; H. E. Boyer, *Secretary,* Managing Editor, Metals Handbook.

For welding titanium thicker than about 0.10 in. by the gas tungsten-arc process, a filler metal must be used. For plasma-arc welding, a filler metal may or may not be used for welding metal less than ½ in. thick.

Filler-metal composition is usually matched to the grade of titanium being welded. For improved joint ductility in welding the higher-strength grades of unalloyed titanium, filler metal of yield strength lower than that of the base metal is sometimes used. For the same reason, unalloyed filler metal has been used to weld Ti-5Al-2.5Sn and Ti-6Al-4V.

The filler metal, as well as the base metal, should be clean at the time of welding. As shown in Fig. 2, wires of the size used for filler metals have a large surface area compared to volume, and therefore if the wire surface is slightly contaminated, the weld may be severely contaminated. Some procedures require that the filler wire be cleaned just before use.

Shielding Gases

Only argon and helium are used for shielding in welding titanium and titanium alloys. Sometimes, a mixture of these two gases is used.

Argon is more widely used than helium because it is more readily available and less costly. Argon was used in each of the four examples presented in this article.

Arc characteristics are affected by the type of shielding gas used. At a given welding current, the arc voltage is much greater with helium than with argon. Because the heat energy liberated in helium is about twice that in argon, higher welding speeds can be obtained, weld penetration is deeper, and thicker sections can be welded more rapidly using helium shielding.

Argon is used in the welding of thin sections, where less heat is required and the arc length can be changed without appreciably changing the heat input. This is a less important factor in automatic welding than in manual welding, because it is easier to control arc length in automatic welding. Helium is often used as the shielding gas at the torch in automatic operations.

Joint Preparation

If welding is done outside a welding chamber, joints must be carefully designed so that both the top and the underside of the weld can be shielded (see the setup in Fig. 1). Dimensions of typical joints are given in Table 1.

For welding titanium alloys, joint fit-up should be better than for welding other metals, because of the possibility of entrapping air in the joint. The joint should be clamped so that no separation occurs during welding.

Cleaning

To obtain a good weld, the joint and the surfaces of the workpieces back at least 1 in. on either side of the joint must be meticulously cleaned. As shown in the flow chart of Fig. 3, the cleaning procedure depends on whether the oxide layer in the joint area is light or heavy.

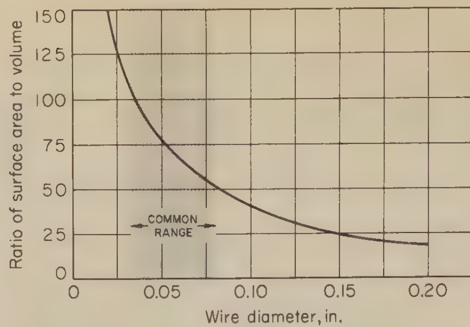


Fig. 2. Ratio of filler-metal (electrode) wire surface area to volume for various wire diameters. Shaded portion indicates range of wire diameters most often used for welding titanium.

Table 1. Dimensions of Typical Joints for Welding Titanium and Titanium Alloys

Base-metal thickness, t, in.	Root opening, in.	Groove angle, deg	Weld-bead width, in.
Square-Groove Butt Joint			
0.010-0.090	0	...	...
0.031-0.125	0-0.10t	...	...
Single-V-Groove Butt Joint			
0.062-0.125	0-0.10t	30-60	0.10-0.25t
0.090-0.125	(a)	90	...
0.125-0.250	0-0.10t	30-60	0.10-0.25t
Double-V-Groove Butt Joint			
0.250-0.500	0-0.20t	30-120	0.10-0.25t
Single-U-Groove Butt Joint			
0.250-0.750	0-0.10t	15-30	0.10-0.25t
Double-U-Groove Butt Joint			
0.750-1.500	0-0.10t	15-30	0.10-0.25t
Fillet Weld			
0.031-0.125	0-0.10t	0-45	0-0.25t
0.125-0.500	0-0.10t	30-45	0.10-0.25t

Source: J. J. Vagi, R. E. Monroe, R. M. Evans and D. C. Martin, "Welding Procedures for Titanium and Titanium Alloys", NASA TMX 53432, 1965

(a) Root face, 0.030 in.

Grease and oil accumulated during forming and machining must be removed before welding to avoid weld contamination. Scale-free metal can be degreased only. Metal with an oxide scale is degreased before descaling. Degreasing can be accomplished by steam cleaning, alkaline cleaning, vapor degreasing, or solvent cleaning.

For vapor degreasing, toluene rather than a chlorinated solvent should be used, because residues from chlorinated solvents (and also from silicated solvents) may contribute to cracking of titanium weldments.

Solvent cleaning is frequently used, especially for large components that cannot conveniently be placed in a vapor degreaser or in a washer for alkaline cleaning. Solvents used include methyl ethyl ketone, toluene, acetone, and other chlorine-free solvents. Methyl alcohol is reported to have caused stress corrosion and is, therefore, prohibited for use on aerospace hardware. The joint areas are hand wiped with the solvent just before welding. All wiping should be done with clean, lint-free cloths or a cellulose sponge. Plastic gloves should be worn; rubber gloves are likely to leave traces of plasticizer, which can cause porosity in the weld metal. Handprints are also a source of contamination.

After a lightly oxidized joint area has been degreased, it should be pickled for a short time. A mixture of 4% hydrofluoric acid and 40% nitric acid (by weight) is typical. Pickling should be done cautiously because hydrogen is detrimental to the properties of titanium, causing embrittlement and sometimes contributing to weld porosity. Industrial practice usually is to maintain the acid bath at a high oxidation potential of 30% or more nitric acid by weight. With nitric acid maintained at 30% by weight, the ratio of HNO_3 to HF is then maintained at 15 to 1 strictly as a factor of safety. (For additional discussion, see "Acid Pickling" on page 665 in volume 2 of this Handbook.) If the nitric acid content falls below 30% by weight and the ratio of HNO_3 to HF falls below 10 to 1, excessive hydrogen pickup is possible.

Lightly oxidized joint areas may also be cleaned by brushing with a stainless steel wire brush or by draw filing. However, if such cleaning methods are used, they should be immediately followed by acid pickling when weld corrosion resistance is important. Steel wool or abrasives should never be used, because of the danger of contamination.

If titanium has been exposed to temperatures above 1000 F, the scale formed is thicker than the scale formed below 1000 F. Removal of the heavier scale requires a more complex treatment. Chemical, salt bath, or mechanical treatments, or combinations of these treatments are used. The salt baths are basically sodium hydroxide to which oxidizing agents or hydrogen have been added to form sodium hydride (see the articles on Salt Bath Descaling and Cleaning and Finishing of Titanium Alloys, beginning on pages 356 and 664, respectively, in Volume 2 of this Handbook).

Two alternative procedures for removing heavy scale are shown by the flow chart in Fig. 3. In one, the parts are subjected to liquid abrasive blasting or salt bath descaling after degreasing. These treatments are usually followed by pickling in nitric-hydrofluoric acid, as for the removal of light scale. When salt bath descaling is used, oxide removal can be hastened by removing the workpieces from the bath, scrubbing them with brushes, and then re-immersing them. To prevent hydrogen pickup during salt bath descaling, time cycles must be short (preferably no more than 2 min) and bath temperature must be carefully controlled.

In the alternative method described in Fig. 3, parts are alkaline cleaned after grease removal (unless alkaline cleaning was used for grease removal), and then pickled, rinsed, and dipped in a sodium dichromate solution.

Selection of cleaning method depends largely on the size and shape of the parts and on the cleaning methods available in a particular plant.

Welding in Chambers

For successful arc welding of titanium and titanium alloys it is necessary to have complete shielding of the weld because of the high reactivity of titanium to oxygen and nitrogen at welding temperatures.

Excellent welds can be obtained in titanium and its alloys in a welding chamber, where welding is done in a protective gas atmosphere, thus giving adequate shielding. Welding in a chamber, however, is not always practical. In manual welding, for example, the location of the glove ports and the presence of a chamber wall impose limitations on visibility, movement and accessibility. This is true to some extent even when the wall is transparent, as in plastic chambers.

For large assemblies, welding in a chamber requires unloading of the chamber after each weldment is completed and loss of purging gas. The chamber must be repurged for welding the next assembly. Such procedures are time consuming and expensive.

Various types of modified chambers have been tried, such as clamp-on chambers.

Welding in Metal Chambers. Welding of titanium was first done in metal chambers that could be evacuated and then backfilled with argon or helium. Such chambers are equipped with glove ports, so that the welder can handle the torch, separate filler metal (if used), and the weldment without admitting air to the chamber, and with viewing ports, so that the welder can see what he is doing.

Generally, shielding gas is not supplied to the welding torch when welding titanium in a metal chamber, and excellent welds can be made if the chamber atmosphere is maintained properly. However, in some applications where heavy or long welds are required, gas is supplied to the torch to improve shielding (see Example 357).

Although metal chambers are expensive to use, especially for large weldments, they often are used in aerospace applications.

With flow-purged chambers, the atmosphere is often tested by welding a piece of scrap titanium before making the assembly weld. The color of the solidified weld metal is observed by gradually pulling the torch away from the molten puddle. The weld-metal colors, in increasing order of contamination, are: bright silver, light straw, dark straw, light blue, dark blue, gray-blue, gray, and white loose powder. A light straw color generally is considered acceptable for all but the most stringent requirements.

To monitor the inert atmosphere continuously, a heated tungsten filament may be placed inside the chamber. Any discoloration of the filament indicates that the purity of the atmosphere has become degraded.

Figure 7 in the article on Gas Tungsten-Arc Welding shows the relation of purging time and gas flow rate to the number of volume changes needed for replacing air with argon in a chamber. Example 133 in the same article describes the welding of a zirconium alloy in a chamber.

In the example that follows, a Ti-6Al-4V hydrofoil center strut subassembly was welded in a metal chamber. This subassembly was part of the complete strut assembly shown at the top in Fig. 4. Procedures for welding the leading-edge and trailing-edge strut subassemblies, and for welding them to the center section, are given in Examples 358 and 359, respectively.

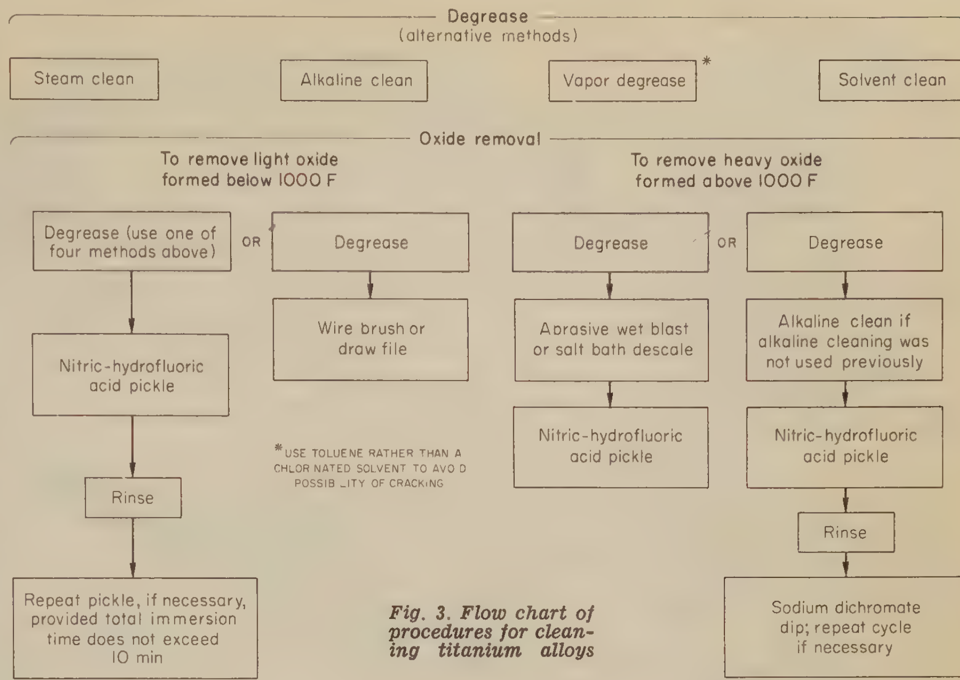


Fig. 3. Flow chart of procedures for cleaning titanium alloys

Example 357. Welding a Hydrofoil Center Strut Subassembly in a Metal Chamber (Fig. 4)

The center strut subassembly of the complete hydrofoil strut assembly shown at the top of Fig. 4 consisted of two machined pieces of Ti-6Al-4V, approximately 112 in. long by 12 in. wide, which were welded by the manual gas tungsten-arc process in a metal chamber 3½ ft in diameter by 24 ft long equipped with four welding ports. The chamber was flow-purged with argon at a slight positive pressure, and was equipped with a fixture-positioner that allowed 360° rotation of the work, if needed, and full conveyance of the workpiece past all of the welding ports. The two components were clamped in a welding fixture, as shown at lower right in Fig. 4, and the fixture was placed in the positioner. The components were clamped at approximately 18-in. intervals along the 112-in. length. Manual welding was used because variations in contour and cross section, limited accessibility, and the small quantity of production weldments that were required ruled out automatic welding.

Before welding, the parts were solution heat treated at about 1750 F, water quenched, and partially aged at 950 F for 4 hr. The joint areas were degreased, alkaline cleaned, and acid pickled in a mixture of concentrated acids (30 volumes of 42° Bé nitric acid and 2 volumes of 70% technical-grade hydrofluoric acid) at room temperature for 5 min. Welding was started within 4 hr after pickling. Workpieces were maintained within the welding chamber until all welds were completed.

The root pass was made without filler metal, to ensure complete root penetration and to minimize burn-through. To obtain the required notch toughness in the joint, the second pass was made with unalloyed titanium filler metal (ERTi-1), although this decreased the strength of the joint slightly. Subsequent passes were made with ERTi-6Al-4V filler metal.

Straight-polarity direct current was supplied from a 300-amp transformer-rectifier with a saturable-core reactor and conventional drooping-voltage characteristic. A foot rheostat controlled the current to the electrode. After welding, the assembly was heat treated at 950 F for 4 hr in argon to complete age hardening, partially relieve welding stresses, and increase weld ductility.

The weld chamber atmosphere was checked periodically by the following tests: weld-bead color, test-coupon weld-bend ductility, dew point, and a heated tungsten filament. All assemblies were examined visually and inspected by dye-penetrant and radiographic methods. Also, representative sample welds were tested mechanically and examined metallographically as a further check on weld quality.

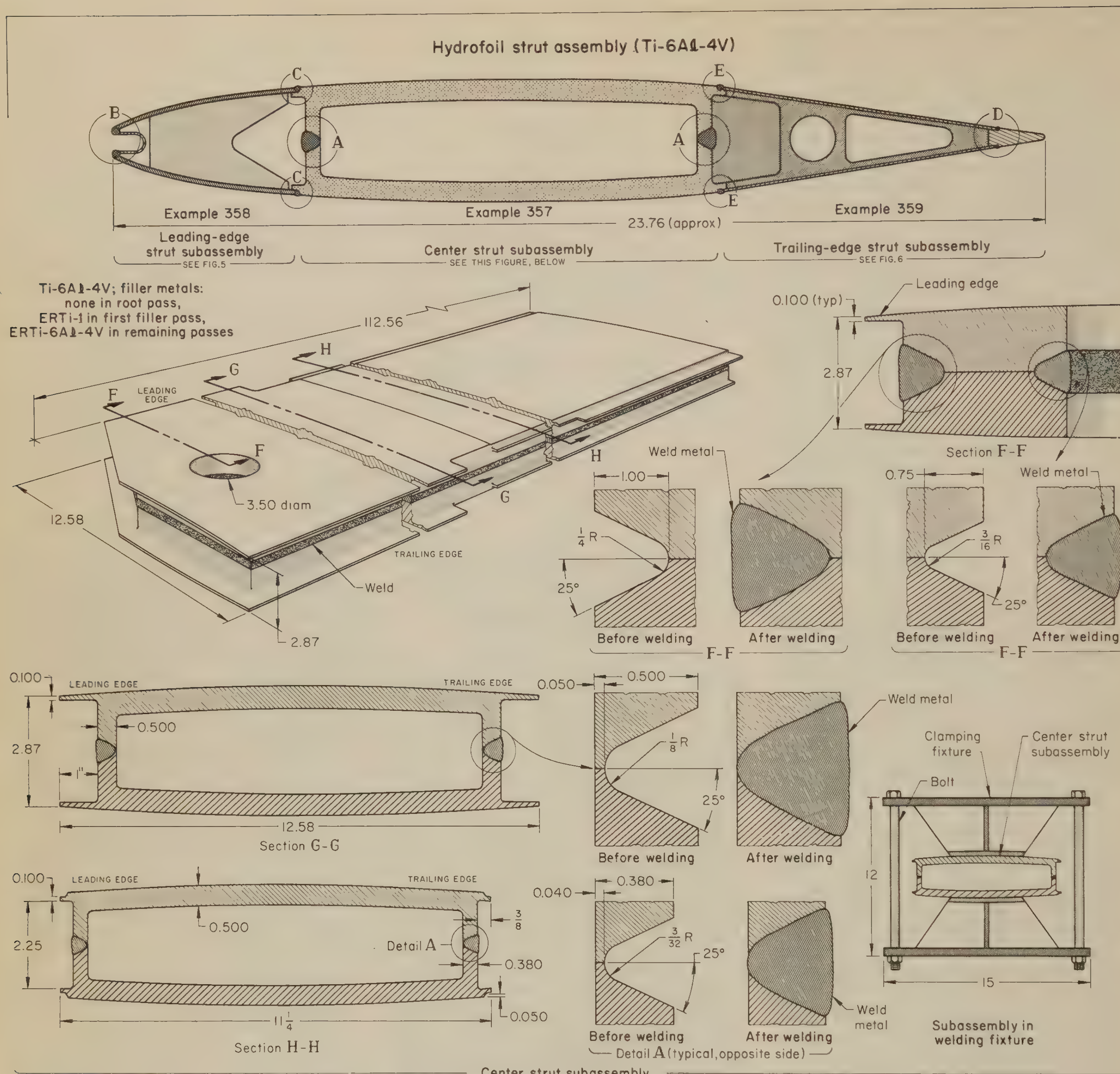
Further details of the welding operation are given in the table with Fig. 4.

Welding in Plastic Chambers. Rigid or collapsible chambers made of transparent plastic can be used where production runs are short, the assembly is large or complicated, and manual welding is required. Rigid plastic chambers are flow-purged with argon or helium, in volumes equal to five to ten times the volume of the chamber, before welding is started. Collapsible plastic chambers are first collapsed and then flow-purged with argon or helium; they require less gas for purging than do rigid chambers.

Advantages of plastic chambers (either rigid or collapsible) are low cost and good visibility of the work. Because there is generally a greater probability of leakage occurring in a plastic chamber than in a metal chamber, the atmosphere must be checked frequently to ensure that it is of proper purity. In addition, torch shielding is usually employed, to make certain that the weld zone is adequately protected. The two examples that follow describe welding in plastic chambers.

Examples 358 and 359. Use of a Plastic Chamber for Welding of Hydrofoil Leading-Edge and Trailing-Edge Strut Subassemblies

A reinforced, collapsible plastic chamber, 3 ft high by 3 ft wide by 20 ft long, having three welding ports, was used for manual gas tungsten-arc welding of hydrofoil leading-edge and trailing-edge strut subassemblies of Ti-6Al-4V alloy and for joining them to a center strut subassembly (see Example 357). The chamber was flow-purged with argon at a slight positive pressure. Purity of the chamber atmosphere was checked by weld-bead color and weld-



Joint type	Butt
Weld type	Single-U groove
Power supply	300-amp, 40-v transformer-rectifier
Shielding gas:	
At nozzle	Argon, at 15 cfh
In chamber	Argon, flowing purge with slight positive pressure
Electrode (EWTh-2) diameter	3/32 in. for sections F-F and G-G; 1/16 in. for section H-H
Torch	350 amp, water cooled
Filler metal:	
Root pass	None
Second pass	3/32 or 1/8-in.-diam ERTi-1
Subsequent passes	3/32 or 1/8-in.-diam ERTi-6Al-4V
Nozzles	9/16 to 3/4-in. ID
Welding position	Horizontal
Number of passes	Various
Type of bead	Convex; stringer
Current:	
Section F-F	150 to 160 amp, dcsp
Section G-G	130 to 140 amp, dcsp
Section H-H	110 to 120 amp, dcsp
Arc initiation	High frequency
Arc length	About 1/8 in.
Welding speed	2 to 4 ipm
Interpass temperature	Not controlled
Postweld heat treatment	4 hr at 950 F, in an argon atmosphere

For details of welding the leading-edge and trailing-edge strut subassemblies and for joining them to the center strut subassembly, see Examples 358 and 359.

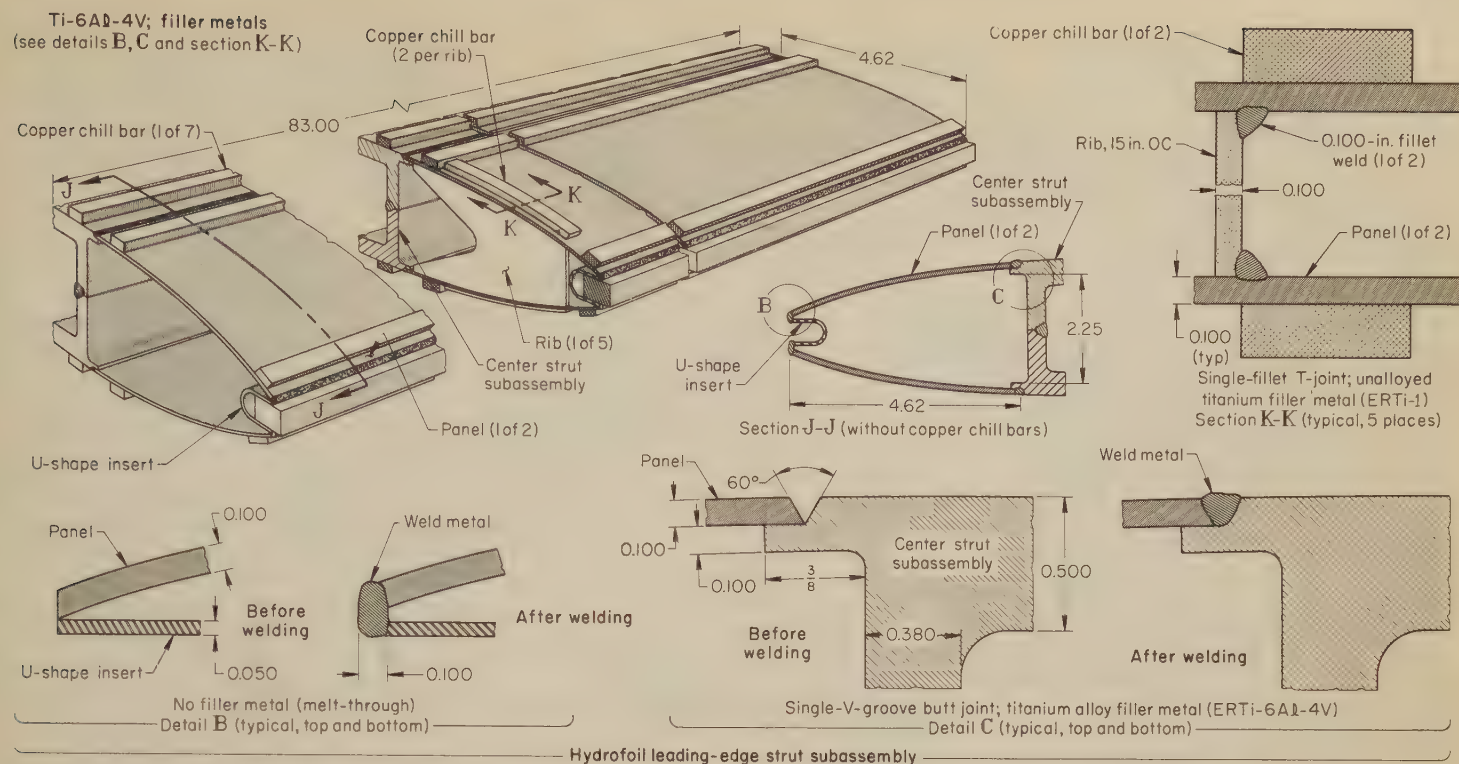
Fig. 4. Center strut subassembly for the hydrofoil shown, welded by the manual gas tungsten-arc process in a metal chamber (Example 357)

bend tests on Ti-6Al-4V test pieces, by a hot tungsten filament in the chamber, and by dew-point measurements.

Manual welding was used because accessibility difficulties and costs precluded automatic welding. All welding was done on components that had been solution treated, water quenched, and partially age hardened (950 F for 4 hr).

Joints were machined smooth, degreased in an alkaline cleaner, and pickled in a mixture of concentrated acids (30 volumes of 42° Bé nitric acid and 2 volumes of 70% technical-grade hydrofluoric acid) at room temperature for 5 min. Welding was started within 4 hr after pickling. Parts remained in the welding chamber until all welds were completed.

Straight-polarity direct current was supplied by a 300-amp transformer-rectifier with a saturable-core reactor and conventional drooping-voltage characteristic. Welding current was controlled with a foot rheostat. Although Ti-6Al-4V has good weldability, copper chill bars were placed adjacent to all welds to increase the cooling rate and improve weld ductility. Chill



Power supply	300-amp 40-v transformer-rectifier, with drooping-voltage characteristic
Chamber	Collapsible plastic, with three ports
Electrode	3/32-in.-diam EWTh-2
Torch	350 amp, water cooled
Fixture	Inexpensive frame
Shielding gas:	
At nozzle	Argon, at 15 cfh
In chamber	Argon, flow-purge with slight positive pressure
Nozzle(a)	9/16-in. ID
Current	120 to 130 amp, dcsp
Voltage	10 v
Arc initiation	High frequency
Arc length	1/8 in. (approx)
Type of bead	Convex; stringer
Interpass temperature	Not controlled
Preheat	None
Postweld heat treatment	4 hr in argon at 950 F

	Detail B	Section K-K	Detail C
Joint type	Edge	T	Butt
Weld type	Square groove	Fillet	V-groove
Filler metal	None	ERTi-1	ERTi-6Al-4V
Filler-metal diameter, in.	None	0.062	0.062
Welding position	Flat	Horizontal	Flat
Passes	One	One	One
Speed, ipm	4 to 6	4 to 6	3 to 5

(a) Occasionally, nozzle was removed for better accessibility to the joint.

For details of welding the center strut subassembly and for view of the completed hydrofoil strut assembly, see Example 357 and Fig. 4. For details of welding the trailing-edge strut subassembly, see Example 359 and Fig. 6.

Fig. 5. Hydrofoil leading-edge strut subassembly welded by the manual gas tungsten-arc process in a plastic chamber (Example 358)

bars were held in close contact with the joint by simple toggle clamps.

After welding, the parts were heated to 950 F and held for 4 hr to complete age hardening, partially relieve stresses, and increase the ductility of the welds.

Welds were examined visually and inspected by dye-penetrant and radiographic methods on each weldment. In addition, representative samples welded at the same time as the production assemblies were tested for mechanical properties and were examined metallographically.

Mechanical properties of the welds were controlled primarily through filler-metal selection, as shown in the following comparison of minimum weld properties (weld metal only) obtained using two different filler metals:

Filler metal	Tensile strength, psi	Yield strength, psi	Elongation, % in 2 in.
Unalloyed Ti	100,000	90,000	5.0
ERTi-6Al-4V	130,000	120,000	4.0

Example 358 — Leading-Edge Strut Subassembly (Fig. 5). Several welds had to be made in a Ti-6Al-4V hydrofoil leading-edge strut subassembly. First, two curved panels, 83 in. long by 4.62 in. wide and 0.100 in. thick, were joined to a U-shape insert, 83 in. long and 0.050 in. thick, by square-groove edge welding (Fig. 5, section J-J and detail B). Next, truncated triangular ribs, 0.100 in. thick, were welded to the panels at 15-in. intervals, using a 0.100-in. fillet weld on one side of each rib (section K-K in Fig. 5). Finally, the open side of the subassembly was welded to the center subassembly (see Fig. 4), using single-V-groove welds (detail C in Fig. 5).

Copper chill bars were used as shown in Fig. 5. Where greater ductility was required, as in the joint shown in section K-K in Fig. 5, unalloyed titanium filler metal (ERTi-1) was used. Where greater strength was required, as in the joints shown in detail C of Fig. 5, ERTi-6Al-4V filler metal was used. Tack welding was employed as needed. Further details of the welding operation are given in the table that accompanies Fig. 5.

For details of welding the center strut subassembly and for a view of the completed hydrofoil strut assembly, see Example 357 and Fig. 4. Details for welding the trailing-edge strut subassembly and for joining it to the center strut subassembly are given in Example 359 and Fig. 6.

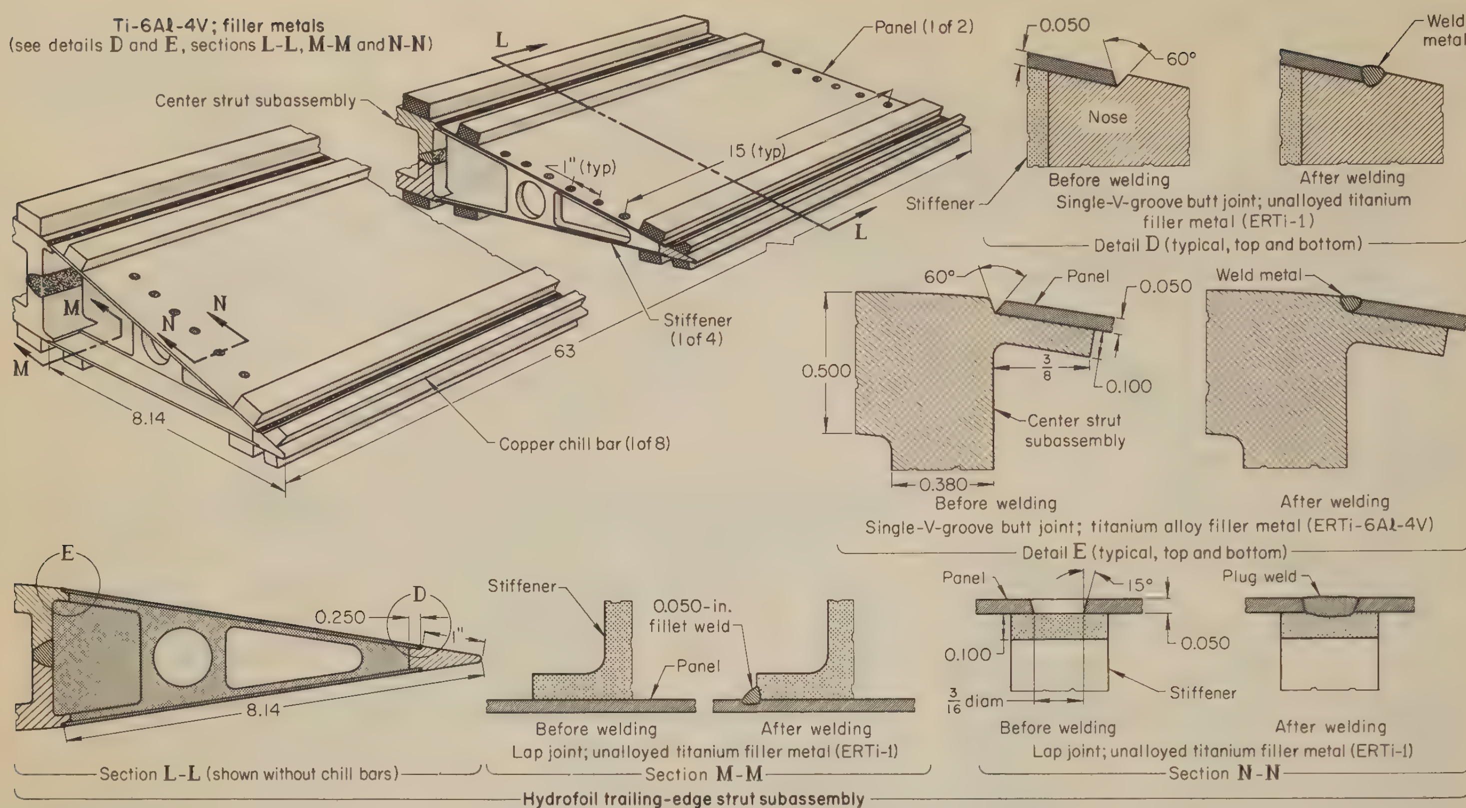
Example 359 — Trailing-Edge Strut Subassembly (Fig. 6). In fabricating a Ti-6Al-4V hydrofoil trailing-edge strut subassembly, two straight panels 63 in. long by approximately 7 in. wide and 0.050 in. thick were welded to a solid triangular piece, as shown in detail D of Fig. 6, using V-groove butt joints. Stiffeners 0.100 in. thick were joined to the panels at 15-in. intervals by fillet welds as shown by section M-M in Fig. 6. The stiffeners were also plug welded to the panels at 1-in. intervals on one side, as shown in section N-N of Fig. 6. The purpose of plug welding was to provide additional stiffener-to-panel attachment in areas where there were no fillet welds because of lack of accessibility. On the side where fillet welds were continuous, no plug welding was needed. Finally, the trailing-edge strut subassembly was welded to the center strut subassembly (detail E, Fig. 6).

Copper chill bars were used adjacent to the butt welds, as shown in Fig. 6. Where good ductility was required, as in the joints shown in detail D and in sections M-M and N-N of Fig. 6, unalloyed titanium filler metal (ERTi-1) was used. Where greater strength was required, as in the joints shown in detail E of Fig. 6, Ti-6Al-4V filler metal was used. Tack welding was employed as required. Further details of the welding operation are given in the table accompanying Fig. 6.

For details of welding the center strut subassembly and for a view of the completed hydrofoil strut assembly, see Example 357 and Fig. 4. Details for welding the leading-edge strut subassembly and for joining it to the center strut subassembly are given in Example 358 and Fig. 5.

Out-of-Chamber Welding

With proper tooling, joints in titanium can be adequately shielded for welding without using a chamber. Both the weld and the heat-affected zones



Power supply	300-amp 40-v transformer rectifier, with drooping-voltage characteristic
Chamber	Collapsible plastic, with three ports
Electrode	1/16-in.-diam EWTh-2
Torch	350 amp, water cooled
Fixture	Inexpensive frame
Nozzle(a)	9/16-in. ID
Voltage	10 v
Arc initiation	High frequency
Arc length	About 3/32 in.
Type of bead	Convex; stringer
Interpass temperature	Not controlled
Preheat	None
Postweld heat treatment	4 hr in argon at 950 F

	Detail D	Sections M-M and N-N	Detail E
Joint type	Butt	Lap	Butt
Weld type	V-groove	Fillet; plug	V-groove
Filler metal	ERTi-1	ERTi-1	ERTi-6Al-4V
Filler-metal diameter, in.	0.062	0.062	0.062
Shielding gas	Argon	Argon	Argon
Flow at nozzle, cfh	10	15	10
Flow in chamber	Purge(b)	Purge(b)	Purge(b)
Current, amp	85 to 95	120 to 130	85 to 95
Welding position	Flat	Horizontal; flat(c)	Flat
Passes	One	One	One
Speed, ipm	4 to 6	4 to 6	3 to 5

(a) Occasionally, nozzle was removed for better accessibility to the joint. (b) Flow-purge with slight positive pressure. (c) Fillet welds were made in the horizontal position; plug welds were made in the flat position.

For details of welding the center strut subassembly and for the completed view of the hydrofoil strut assembly, see Example 357 and Fig. 4. For details of welding the leading-edge strut subassembly, see Example 358 and Fig. 5.

Fig. 6. Hydrofoil trailing-edge subassembly welded by the manual gas tungsten-arc process in a plastic chamber (Example 359)

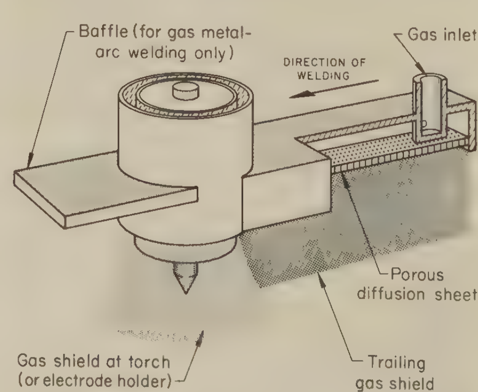
must be shielded during welding and until the temperature of the metal in the area of the weld is below 1000 F. If shielding is inadequate, the welds will be brittle.

The welding torch (or electrode holder) is usually equipped to supply a trailing shield that provides a diffuse, nonturbulent flow of gas to the solidifying weld. A typical trailing shield is shown in Fig. 7. The length of the trailing shield must be adjusted to the speed of welding. Both straight and curvilinear welding can be shielded. The welding station must be shielded by curtains to prevent drafts.

In the following example, titanium alloy straps were welded in air — with adequate shielding — when production in a clamp-on chamber proved clumsy and time consuming.

Example 360. Welding Ti-6Al-4V in Air, Using a Continuous, Enveloping Flow of Argon (Fig. 8)

Because of their length (36 to 42 ft), Ti-6Al-4V fail-safe straps for C-5A transport airplanes were made by welding together two or more pieces, using the manual gas tungsten-arc process. A typical 6-in.-wide joint in a 40-ft-long by 0.188-in.-thick fail-safe strap is shown in Fig. 8 (upper left). Because the straps were too long for the available vacuum welding chamber, a special shielding method had to be developed.



The baffle shown on the leading side of the torch (or electrode holder) is seldom used for gas tungsten-arc welding, but it is used for gas metal-arc welding (see the section in this article on Gas Metal-Arc Welding).

Fig. 7. Arrangement for shielding in automatic welding of titanium alloys in air

The first attempt at providing adequate shielding was to construct a clamp-on displacement chamber, approximately 3 ft long, 2 ft wide and 2 ft high. This chamber contained glove ports, a viewing port, an argon flow control system, a flapper valve for venting excess gas pressure, a feedthrough plate for torch leads, and slots at both ends for the fail-safe straps to pass through. Several straps were manually gas tungsten-arc welded in the chamber, and although weld quality was satisfactory, it was apparent that this method of shielding was too clumsy and time consuming for production use.

A second method, based on flooding the immediate area of the 6-in.-long weld with a continuous flow of argon, proved successful (Fig. 8, left and section B-B), and was simpler to operate. The joint to be welded was centered over the groove of a copper backing bar that was set flush with the surface of a long aluminum support plate (Fig. 8, section B-B). The entire assembly was placed on a long welding table. Next, two copper hold-down bars were bolted tightly in place, ½ in. on either side of the joint. The hold-down bars and the backing bar had been drilled so that shielding gas could be supplied by manifolding arrangements, as shown in Fig. 8 (view at bottom left, and section B-B). This tooling provided a heat sink, good joint alignment, effective gas shielding, and a high degree of

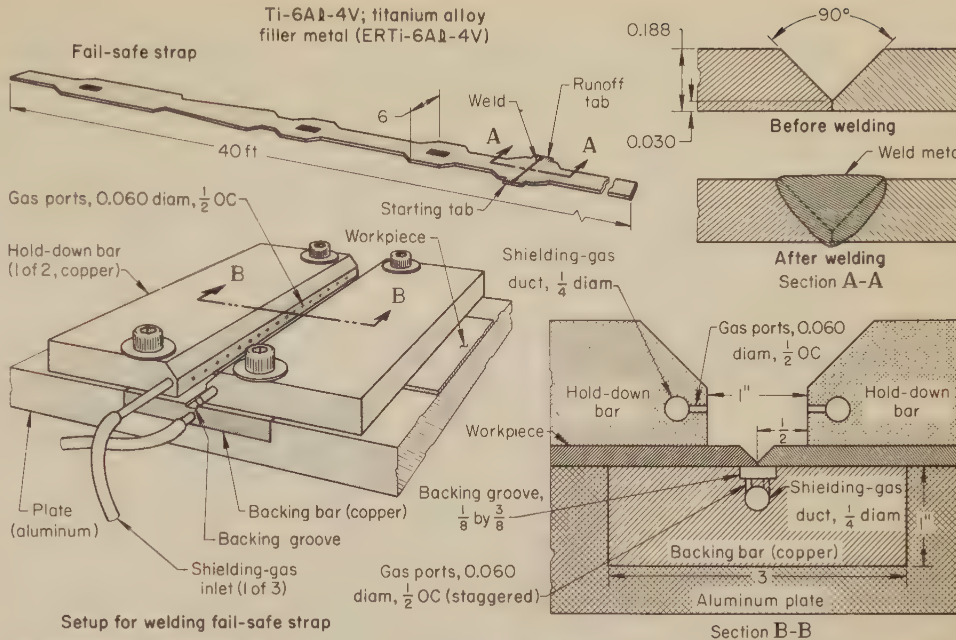
accessibility. Additional argon shielding gas was supplied through the torch.

Joints were provided with integral starting and runoff tabs. A tack weld was placed on the runoff tab, and welding was started at the opposite end and completed in a single pass, using the forehand technique (filler metal preceded the torch in the direction of welding). Details of the cleaning and welding operations are summarized in the table that accompanies Fig. 8.

First results, which were used to qualify the procedure, were quite satisfactory. On both sides, the weld color resembled that of newly minted silver. Radiographic and dye-penetrant examination showed no defects. Specimens bent over a 6*t* (1⅛ in.) radius showed no cracks on the outer surface at a magnification of 10×. All tension-test specimens failed in the base metal at 135,000 psi or more.

Specifications called for testing three preproduction specimens and one postproduction specimen per lot. The first production lot consisted of 16 straps. The test specimens and the 16 production welds were inspected by visual, radiographic and dye-penetrant methods. All welds were acceptable under visual and dye-penetrant examinations, and only two production welds showed slight porosity (which could be repaired) under radiographic examination. Two bend-test specimens and one tension-test specimen were machined from the postproduction weldment. Bend tests showed no cracks at 10× magnification, and the tension-test specimen failed in the base metal at 140,000 psi.

In general, welds made with this shielding technique were comparable in quality to those obtained in a conventional welding chamber, and better than those obtained in the clamp-on displacement chamber. Making a weld in the clamp-on displacement chamber required 60 min and 100 cu ft of argon, compared to 10 min and 15 cu ft of argon for the out-of-chamber technique.



Preweld Cleaning

Degrease	In hot alkaline cleaner, 15 min; brush; rinse in hot tap water
Pickle	In solution of 20% nitric acid – 3% hydrofluoric acid, 30 sec; rinse in hot, then cold, tap water
Final rinse	In deionized water; dry; weld within 4 hr or reclean

Conditions for Gas Tungsten-Arc Welding

Joint type	Full-penetration butt	Shielding gas:	
Weld type	90° single-V groove(a)	At nozzle	Argon, at 20 cfh
Filler metal	⅛-in.-diam ERTi-6Al-4V	Through backing bar	Argon, at 15 cfh
Current	155 to 195 amp, dcsp	Through hold-down bars	Argon, at 40 cfh
Voltage	12 to 16 v	Welding time	About 4.5 min per joint

(a) With 0.030-in. root face

Fig. 8. Tooling setup for supplying shielding gas to the weld area for gas tungsten-arc welding of the military fail-safe strap shown (Example 360)

Equipment for Gas Tungsten-Arc Welding

Transformer-rectifiers are the preferred power supply for welding titanium, because the current can be controlled more closely than with motor-generator sets; slight variations in welding current may cause variations in penetration.

Straight-polarity direct current (dcsp) is always used for gas tungsten-arc welding of titanium because deeper weld penetration and a narrower bead can be obtained than with reverse-polarity direct current (dcrp). Also, in manual welding, straight-polarity current is easier to control.

The power supply should also include accessories for arc initiation because of the danger of tungsten contamination of the weld if the arc is struck by touch starting. If welding is to be done in air, controls for extinguishing the arc without pulling the torch away from the workpiece are needed, so that shielding-gas flow will continue and the hot weld metal will not be contaminated by air. For further details on power supplies and other equipment, see the article on Gas Tungsten-Arc Welding, pages 113 to 137.

Electrodes for welding titanium are of the conventional thoriated tungsten type (EWTh-1 or EWTh-2). The electrode tip is tapered to improve arc initiation and control the spread of the arc.

Shielding. To ensure a diffuse, nonturbulent flow of shielding gas, nozzles of the torches for welding titanium are larger than those used for welding other metals. With a 1/32-in.-diam electrode, a 9/16-in.-ID nozzle is ordinarily used, and with a 1/16-in.-diam electrode, a ¾-in.-ID nozzle. Phenolic or other plastic nozzles should not be used, because there is danger of contaminating the weld with carbon.

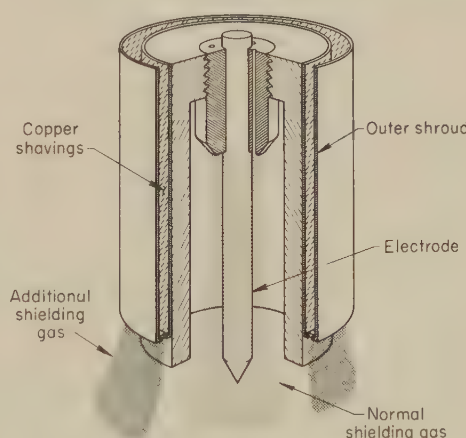


Fig. 9. Sectional view of a torch nozzle equipped with an outer shroud containing copper shavings to provide additional gas shielding for manual inert-gas welding

Because titanium has low thermal conductivity, the area ahead of the arc does not get heated above 1000 F, and therefore leading shields are seldom required when welding is done by the gas tungsten-arc process. For welding operations where a trailing shield such as shown in Fig. 7 is not adaptable, the nozzle of the torch is fitted with a concentric outer shroud through which is fed a supplementary supply of shielding gas. Such a torch is shown in Fig. 9. Here shielding gas is diffused through copper shavings, contained in the outer shroud, which cool the gas substantially, helping to protect the metal near the weld.

Shielding of the underside of a weld is provided by slotted backing bars, usually copper, through which a diffuse flow of argon or helium is maintained (see Fig. 1 and 8). Gas channels in the clamping fixtures also provide diffuse flow of inert gas to the weld area. These fixtures are placed close to the weld so that there is no danger of air contamination (see Fig. 8).

Fixtures. Copper fixtures are usually used. Other metals are sometimes used, but they should be nonmagnetic; otherwise, arc blow is likely to occur. Metal fixtures sometimes are water cooled, although water cooling introduces the possibility of moisture from the air condensing on the fixtures.

Procedures for Gas Tungsten-Arc Welding

Generally, procedures for gas tungsten-arc welding of titanium alloys are similar to those used for austenitic stainless steel.

Preheating. Titanium alloys do not require preheating. Although cracking may occur in titanium alloy weld-

Table 2. Typical Conditions for Manual and Automatic Gas Tungsten-Arc Welding of Ti-6Al-4V (a)

Metal thickness, in.	Filler-metal diameter, in.	Electrode diameter, in.	Shielding gas(b), and flow rate, cfh: Nozzle	Trailing	Backing	Current (dcsp), amp	Voltage, v	Welding speed, ipm
Manual Welding								
0.050	None	0.062	A, 10	A, 20	A, 3	65	9	...
0.070	None	0.062	A, 15	A, 25	A, 6	90	9	...
Automatic Welding								
0.060	None	0.062	A, 15	A, 30	A, 4	95	10	10
	0.062	0.062	A, 15	A, 40	A, 5	125	10	12
0.125	None	0.062	He, 65	He, 60	A, 15	85	14	3

(a) Flat-position welding. (b) A = argon; He = helium.

ments, it is most often related to contamination, and cannot be prevented by preheating. Also, there is no need for maintaining a specific interpass temperature.

Tack welding is used to pre-position parts or subassemblies for final welding operations. Elaborate fixturing often can be eliminated when tack welds are used to their full advantage. Various tack welding procedures can be used, but in any procedure good cleaning practices and adequate shielding must be provided to prevent contamination of the welds. Contamination or cracks developed in tack welds can be transferred to the finish weld. One procedure is to tack weld in such a way that the finish weld never crosses over a previous tack weld. To accomplish this, sufficient filler metal is used in tack welding to completely fill the joint at a particular location. The finish weld beads are blended into the ends of the tack welds.

Arc Length. As with stainless steel and the nickel-base alloys, the maximum arc length for welding without filler metal should be about equal to the electrode diameter. With longer arc length, there is danger of turbulence, which may draw air into the weld puddle. Also, long arc length produces wider weld beads than short arc length.

When filler metal is used, the maximum arc length should be about 1½ times the electrode diameter, depending on the thickness of the base metal.

Welding Conditions. Conditions that have been used for gas tungsten-arc welding of Ti-6Al-4V sheet are given in Table 2.

In welding titanium alloys, it is best to use a heat input just above the minimum required to produce the weld. If a greater heat input is used, the possibility that the weld will become contaminated, distorted or embrittled is increased.

Avoiding porosity in welds is an important consideration in welding titanium alloys. If the joints and filler wire are properly cleaned and the tooling does not chill the weld too rapidly, porosity can be reduced or eliminated by using a slower welding speed, which will retard weld solidification and allow entrained gases to escape.

Gas Metal-Arc Welding

Gas metal-arc welding is normally used for welding titanium and titanium alloys ⅛ in. or more thick. It has been used to a considerable extent for welding ½-in. plate.

Metal transfer through the arc in gas metal-arc welding can lead to difficulty in meeting stringent aerospace quality requirements. For example, weld spatter is often associated with inferior weld quality, and arc instability, which can occur in gas metal-arc welding, is a potential cause of weld contamination and defect formation. Some users of titanium alloys prefer gas tungsten-arc welding over gas metal-arc welding (even for joining thick plate), because with the gas tungsten-arc process more uniform and predictable transverse shrinkage is obtained.

Electrode wires for gas metal-arc welding are available in several grades of unalloyed titanium and in titanium alloys that match the composition of the base metal.

Joint preparation and cleaning procedures are the same as those described earlier in this article.

Typical conditions for gas metal-arc welding of Ti-6Al-4V and Ti-5Al-2.5Sn plate are given in Tables 3 and 4.

Table 3. Typical Conditions for Manual and Automatic Gas Metal-Arc Welding of Ti-6Al-4V Plate (a)

Plate thickness, in.	Current (dcrp), amp	Voltage, v	Welding speed, ipm	Argon flow rate, cfh: Torch	Trailing	Backing
Manual Welding						
0.625 ...	310	38	...	36	(b)	(b)
2.00(c) .	310	38	...	36	(b)	(b)
Automatic Welding						
0.625(c) .	360	45	15	50	60	6
2.00(c) .	325	33	25	(d)	(d)	(d)

(a) Using a 0.062-in.-diam electrode. (b) Not reported. (c) Multiple passes. (d) Argon chamber.

Table 4. Typical Conditions for Gas Metal-Arc Welding of ½-In.-Thick Ti-5Al-2.5Sn Plate

Electrode wire	1/16-in.-diam ERTi-5Al-2.5Sn
Wire-feed rate	300 ipm
Current	300 amp, dcrp
Voltage	30 v
Nozzle	1-in. ID
Backing bar	Copper; with 1/16-in.-deep by ¼-in.-wide groove
Shielding-gas flow:	
At torch	Argon, at 50 cfh
Trailing	Argon, at 50 cfh
Backing	Helium, at 20 cfh
Welding speed	20 in. per minute

Table 5. Stress-Relieving Times and Temperatures for Six Titanium Alloys

Grade	Temperature, F	Time, hr
Unalloyed Ti-0.15Pd	800	8
	900	¾
	1000	½
Ti-5Al-2.5Sn(a)	900	20
	1000	6
	1100	2
	1200	1
Ti-6Al-4V:		
Annealed(a)	900	20
	1000	2
	1100	1
Solution treated	900	15
	1000	4
Aged	900	15
	1000	5
Ti-8Al-1Mo-1V:		
Single and double annealed	1100	2
	1200	1½
	1300	½
Triple annealed	1100	5
	1200	2
	1300	½
Ti-5Al-5Sn-5Zr	1200	3
	1300	½
Ti-7Al-12Zr	1200	3
	1300	¾

(a) Data apply also to extra-low-interstitial (ELI) modification of the two alloys noted.

Shielding for out-of-chamber welding is provided by inert gas being fed through the nozzle of the electrode holder, through the backing bar or plate, and as a trailing shield, much as in gas tungsten-arc welding (see Fig. 7). The electrode holder is basically the same as the holder used for gas metal-arc welding of steel (see the article on Gas Metal-Arc Welding, which begins on page 78). To avoid contamination and porosity in gas metal-arc welding, it is necessary to have a leading shield as well as a trailing shield, and a suitable baffle added on the leading edge of the electrode holder (see Fig. 7). A leading shield prevents oxidation of spatter before it is melted in the weld metal.

Plasma-Arc Welding

Plasma-arc welding, described in detail in the article on that process, beginning on page 138, has been used successfully for joining titanium alloys. Table 7 and Example 141 in that article present typical operating conditions for plasma-arc welding of Ti-6Al-4V.

Stress Relieving

Most titanium weldments are stress relieved after welding to prevent weld cracking and susceptibility to stress-corrosion cracking in service. Stress relief also improves fatigue strength.

An assembly subjected to a substantial amount of welding and severe fixturing restraint may require intermediate stress relieving of the partially welded structure, which should be done in an inert atmosphere; otherwise, the unwelded joints may have to be recleaned before being welded.

With unalloyed titanium and alpha titanium alloys, time and temperature should be controlled to prevent grain growth. Stress relieving times and temperatures for several weldable titanium alloys are given in Table 5.

For alloys not mentioned in Table 5, tests should be conducted to make certain that stress relieving does not reduce fracture toughness, creep strength, or other property of importance.

Stress relieving of Ti-13V-11Cr-3Al weldments causes aging and subsequent embrittlement of the weld and heat-affected zone, and is not recommended. Re-solution heat treatment (re-annealing) may be used to relieve stresses if the welded assembly is amenable to such treatment. Contaminated surface metal must then be removed from the entire weldment by machining or descaling and pickling to remove 0.001 to 0.002 in. per surface. Mechanical stress relief of Ti-13V-11Cr-3Al weldments is sometimes feasible.

ELECTROSLAG AND ELECTROGAS WELDING

CONTENTS

Electroslag Welding

ELECTROSLAG WELDING is a process in which heat from a layer of molten flux (slag) melts a consumable electrode and the surface of the base metal to produce a weld puddle. Filler metal (the electrode) is fed into a molten flux pool contained in a pocket formed by copper shoes or dams (water-cooled or not) that bridge the gap (joint) between the members being welded. The process utilizes the electrical resistivity of the molten flux to produce continuously the heat needed to melt the filler metal and adjacent base metal. Throughout the progress of welding, the molten flux maintains a protective cover over the joint.

Although the axis of the weld joint is vertical, the process is actually flat-position welding with vertical travel; the consumable electrode is fed downward, through a guide tube, into a cavity formed by the pieces being welded and one or more dams (see Fig. 2).

In its mechanical aspects, electroslag welding resembles electrogas welding (see the article on Electrogas Welding, which begins on page 395), but the electrical characteristics of the two processes differ in two important respects: (*a*) electrogas welding is an arc welding process, whereas in electroslag welding, an arc is used only at the start of welding; when the flux is melted, it chokes the arc, and the filler metal and the surface of the base metal are melted by the heat produced by the electrical resistance of the molten flux; and (*b*) either alternating or direct current is used for electroslag welding, whereas only direct current is used for electrogas welding.

The process described above is generally referred to either as the conventional system of electroslag welding, or simply as electroslag welding.

Electroslag Welding by the Consumable-Guide-Tube System. Consumable-guide-tube electroslag welding, a modification of the conventional system, is a method of electroslag welding in which filler metal is supplied by the electrode and its guiding member (see Fig. 3). The electrode wire (filler metal) is fed to the weld puddle through a tube that is also consumable. The use of a consumable guide tube obviates the need for vertical travel of the welding head, thus simplifying equipment.

The mechanical aspects of the two systems are described in greater detail in the section in this article on Principles of Operation. For the most part, the two systems are capable of producing similar results, although there are applications for which one is better suited than the other (see the section on Conventional System vs Consumable-Guide-Tube System, on page 393).

Applicability

Although most applications of electroslag welding involve the welding of low-carbon steel, the process is also used extensively for welding medium-carbon steels such as 1045 and 1050, and to a lesser extent for welding high-strength structural steels. The electroslag process has also been successfully used for welding high-strength alloy steels such as D-6ac, stainless steels, and nickel alloys.

Thickness Range. Electroslag welding (both systems) is most often used for welding plate from 1¼ to 12 in. thick. In a few applications, the process has proved advantageous for welding plate ⅜ in. thick. No upper thickness limit has been reached; steel sections 36 in. thick have been joined successfully by electroslag welding.

The lower limit of plate thickness depends mainly on costs compared with other processes. Submerged-arc welding and electrogas welding are usually alternative processes for welding plate less than 2 in. thick. In some plants, a 1¼-in. thickness has been established as the economic break point between submerged-arc or electrogas welding on the one hand and electroslag welding on the other, assuming that the joint can be satisfactorily welded by all three processes. In other plants, the break point is considered to be at a thickness of ¾ in. Each application requires careful cost analysis to determine the most economical process.

Length of Joint. The maximum length of joint that can be welded by the conventional system is limited only by the auxiliary equipment available. For the consumable-guide-tube system, there are other limitations (see the section on Conventional System vs Consumable-Guide-Tube System).

Types of Joints Welded. Butt joints between plates of equal thickness are those most readily, and hence most frequently, welded by the electroslag process. When other types or configurations of joints are welded, special dams or special techniques, or both, are usually required. Figure 1 shows several joints that have been successfully welded by the electroslag process.

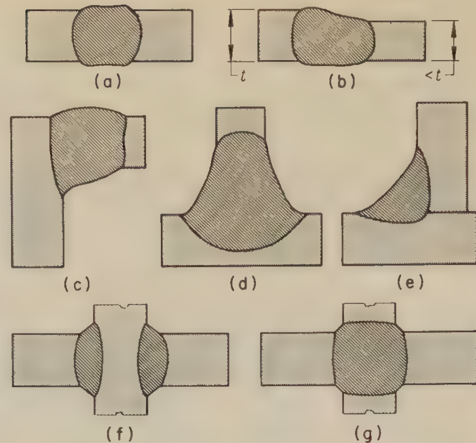
Circumferential welding can be done by the electroslag process, with the use of special techniques (see the section on Circumferential Welding in this article, page 389).

Specific Applications. Welding of thick steel plate, heavy steel forgings, and large steel castings comprises the principal field of application for electroslag welding. In structural applications, electroslag welding is used to fabricate heavy and massive members in the shop for use in structures such as large buildings.

Cylinders and rings for products such as gear blanks, motor frames, press frames, crusher bodies, pressure vessels, and tires for road rollers comprise another important group of applications for electroslag welding. Such parts are formed from plate and welded along a longitudinal joint. In many applications, electroslag welding has replaced submerged-arc welding (heretofore the method most often used for welding such shapes), with a substantial reduction in fabrication time (see Examples 364 and 365). In one application of welding a cylinder having a 42-in. inside diameter and a 2¼-in.-thick wall, welding time using the electroslag process was one-fourth the time required using the submerged-arc welding process.

In the manufacture of large presses and machine tools, electroslag welding has been used for splicing two or more large, thick plates when it was impossible to purchase single plates that were large enough (see Example 363). One manufacturer spliced plates 8 in. thick by 12 ft wide to make a large press frame. When the joints had been welded by the shielded metal-arc process, welding required 80 hr, and turning the plates took a considerable amount of time. With electroslag welding, the joint was welded in 4.2 hr, and no time was required for handling other than setup.

Because of the high deposition rate and relatively low cost of electroslag welding, weldments are now used where they had been previously considered impractical or too expensive. For example, the demand for large steel castings (200,000 lb or more) is increasing, but castings of this size are beyond the capacity of most foundries to produce. If large, complex castings can be divided into less complex components, there is a reduction in the cost of patterns and molding, and with electroslag welding, they can be joined to produce a weldment that is the structural equivalent of the large casting. Various wrought elements can also be incorporated into the weldment instead of using all castings, thereby simplifying assembly and reducing material costs (see Examples 361 and 362).



(a) Butt; square-groove weld. (b) Butt; square-groove weld, transition between two plates of different thicknesses. (c) Corner; square-groove weld. (d) T; square-groove weld. (e) Corner; fillet weld. (f) Double-T; two square-groove welds. (g) Modified butt; square-groove weld.

Fig. 1. Seven joint-weld combinations made by the electroslag process

Principles of Operation

Electroslag welding is a progressive process of melting and solidification in which heat generated by the passage of current through a layer of molten flux is used to melt the filler metal and the surfaces of the workpieces being welded. The current is conveyed into the flux through the consumable electrode. Welding current flows between the electrode and base metal, maintaining the flux at a temperature determined by the electric power transmitted. Fluxes compounded to provide the desired melting temperatures, viscosity and electrical resistivity are essential for satisfactory operation. The main principle of operation is the same for both methods of electroslag welding — metal transfer is arcless.

Electroslag welding can be started by initiating an arc beneath a layer of granular welding flux, much the same as in submerged-arc welding, or by initiating the arc on steel wool and immediately adding flux. As soon as a sufficiently thick layer of flux is melted, all arc action stops and current passes from the electrode to the metal being joined, through the conductive flux, and the process becomes electroslag welding.

Welding in a vertical direction, using retaining dams to mold the molten metal, results in solidification that is highly directional, and nonmetallics are rejected upward into the flux pool.

In submerged-arc welding, the arc, submerged under powdered granular flux, creates the heat necessary for welding. The voltage across the arc ranges from 25 to 32 volts. Depth of flux is not sufficient to block arc action. In electroslag welding, the flux pool is 1½ to 2 in. deep, and because it offers a conductive path for the flow of electric current between filler-metal wire and base metal, the molten flux can extinguish the arc without breaking the current flow.

To heat the flux sufficiently, higher voltages (about 40 to 55 volts) are used than in submerged-arc welding. High deposition rates, together with constant joint widths, make it possible to join thick sections that were formerly impractical to weld.

Conventional Electroslag Welding. The equipment for welding and a detailed view of a joint being welded by the conventional process are presented in Fig. 2. The sectional view of the joint shows typical depths of molten weld metal and molten flux. In Fig. 2, two guide tubes and two sets of electrode-wire feed rolls are shown. One, two or three guide tubes and sets of feed rolls are commonly used, depending on base-metal thickness, although more may sometimes be required.

The electrode-wire guides are maintained just a short distance (½ to 2 in.) above the molten flux. This distance is controlled by moving the entire welding machine upward at a pre-established rate that is consistent with the deposition rate. Movement can be accomplished by chains lowered from an overhead mechanism, or the welding machine can be moved on a vertical track or rail. The mechanism for providing vertical movement of the welding machine is not shown in Fig. 2.

The rate of vertical travel can be controlled by several means. It can be controlled manually by the welding operator. More often, however, it is controlled by a signal from a photoelectric cell that is focused across the flux pool. As the flux pool rises, the photoelectric cell signals a drive motor that moves the entire unit upward to

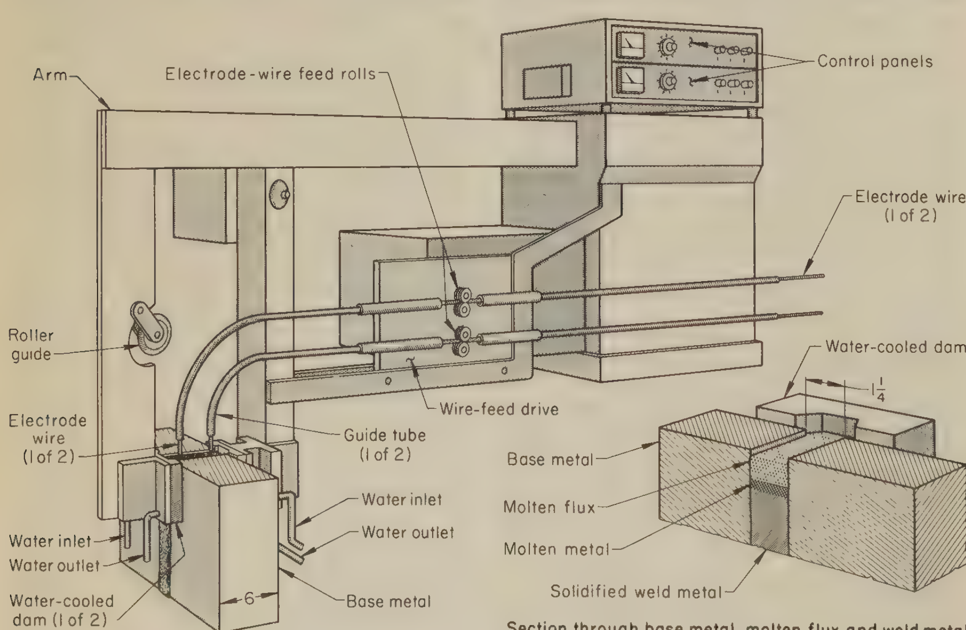


Fig. 2. Principal components and setup of equipment for conventional electroslag welding. The mechanism for providing vertical movement of the welding machine is not shown.

maintain proper relationship of wire guides and flux pool. Irrespective of the mechanism used to control vertical travel, some adjustments are usually required by the welding operator during the early stages of welding, to establish the required travel speed.

As shown in Fig. 2, the electrode wires are fed through the guide tubes by feed rolls. Although electrode feed is automatic, speed must be preset. It may also require adjustment by the welding operator until the operation is established. Current is conducted to the electrode wire by the guide tubes, the guide tubes serving the same purpose as the contact tube in an electrode holder for gas metal-arc welding. The electrode wires (and guide tubes) may or may not be oscillated (moved horizontally back and forth in a direction parallel with the edges of the workpiece) during welding, depending on the thickness of the work metal and the number of electrodes used.

The water-cooled dams (mold shoes) are attached to the welding machine and move vertically as the machine moves. The dams serve three purposes: (*a*) they serve to contain the molten weld metal until it solidifies and to contain the molten flux; (*b*) they accelerate solidification of the weld metal; and (*c*) they mold the outside contours of the joint to give desired reinforcement.

Electroslag Welding by the Consumable-Guide-Tube System. With the consumable-guide-tube system, the mode of metal transfer is also arcless. The principal difference from the conventional system is that none of the welding-machine components moves upward during the welding operation; the only vertical movement is that of the electrode wire through the feed rolls and guide tube (vertical down).

As shown in Fig. 3, the main components are: power supply, control panel, wire-feed drive, consumable guide tube, and water-cooled dams. The wire is fed vertically through the consumable guide tube to the pool of molten flux. At the beginning of welding, the consumable guide tube is lowered to within 1½ in. of the bottom of the joint; it melts off as the level of the weld rises. Welding begins by arcing between the electrode wire and the base metal, or steel wool, as in the conventional system. As soon as the flux pool is established, it extinguishes the arc and welding proceeds in a vertical direction. Most of the filler metal is supplied by the electrode wire, but about 5 to 10% is supplied by the consumable guide tube.

In this system of electroslag welding, the water-cooled dams (mold shoes) are separate from the other equipment. They are held in place by wedges between the dams and strongbacks, as shown in Fig. 3. For welding a short joint, one set of dams may be enough, but more commonly two sets are used, the bottom set being removed from the joint when the weld metal has solidified and being placed above the other set. As welding proceeds, the dams are moved ("hopped") as required.

Although a single wire feed is shown in Fig. 3, multiple wire feeds are often used. Wire can be oscillated if required, as in the conventional system.

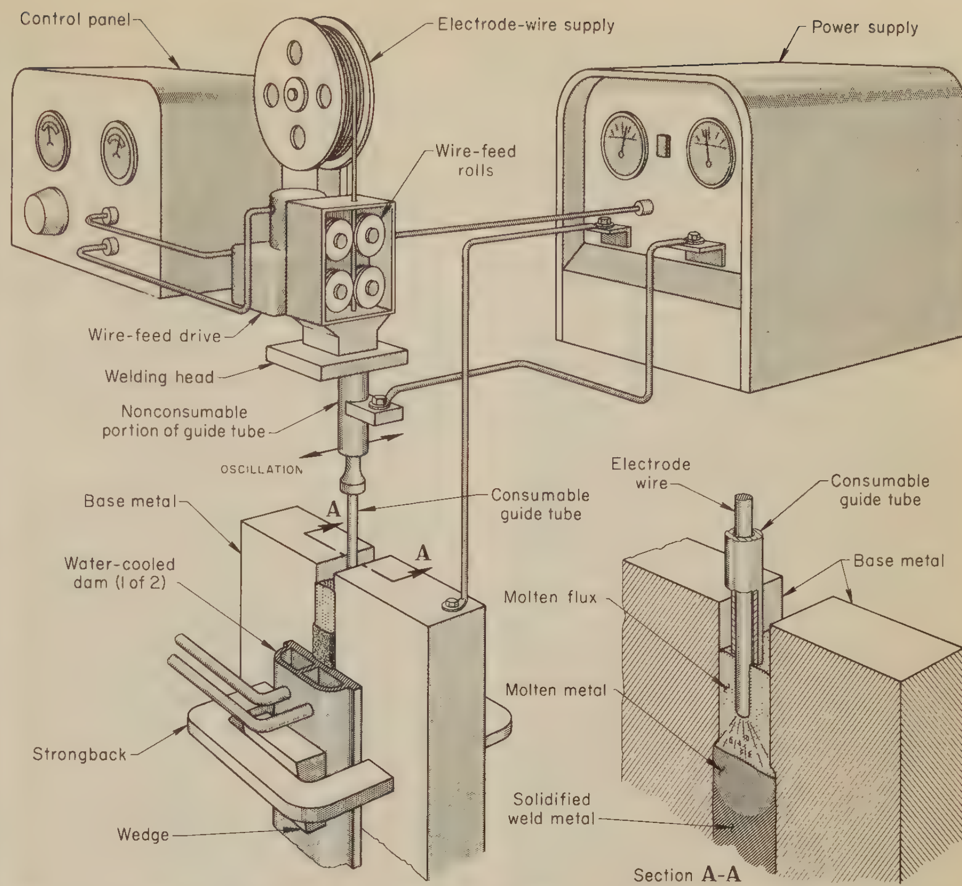


Fig. 3. Principal components and setup of equipment for electroslag welding with the consumable-guide-tube system

Equipment

Constant-voltage transformer-rectifiers are used extensively to supply the power for electroslag welding (both systems), because they are easily controlled and because they are standard in many plants, being used for gas metal-arc and flux-cored arc welding. The power rating of a machine is usually 750 amp, 60 volts at 100% duty cycle. A power supply of this rating is required for each wire fed; thus, total capacity for welding with three electrode wires would be 2250 amp.

Constant-current transformer-rectifiers have been successfully used for electroslag welding, but they are more difficult to control. Their ready availability has usually been the principal reason for their use.

Motor-generators have also proved satisfactory for electroslag welding. However, motor-generator sets having a capacity of 750 amp at 100% duty cycle are far more costly than transformer-rectifiers of this capacity.

Alternating current supplied by transformers has been more extensively used in Europe than in the United States and Canada (see Example 365).

Guide Tubes (Conventional System). The nonconsumable guide tubes shown in Fig. 2 may be identical with the electrode holders used for electrogas welding (see the discussion under the heading "Electrode holders" and Fig. 2 on page 396, and Fig. 3 on page 397). The guide is a beryllium copper tube supported by two narrow rectangular bars brazed to it. The tube and supports are then wrapped with insulating tape. Because the guide tube is positioned close to the molten flux, the end will deteriorate. The end can be cut off and the guide used where a shorter one will suffice (note in Fig. 2 that the curved guide tubes have different lengths).

A guide tube must be narrow enough to clear the plates being welded as it passes vertically between them, and preferably with clearance to spare, especially when the guide is oscillated. Nonconsumable guide tubes are usually less than ½ in. in diameter.

Guide Tubes (Consumable-Guide-Tube System). The nonconsumable portion of the wire guide (where the power is connected, as shown in Fig. 3) is usually made from a copper alloy. Because the consumable portion becomes a part of the weld, it is made from a steel that is compatible with the base metal being welded. The guide tubes are commonly ⅝ in. in outside diameter and ⅛ to 3⁄16 in. in inside diameter, although guide tubes with an outside diameter of less than ⅝ in. are available and are necessary for welding sections thinner than ¾ in. Guide tubes are available in various lengths.

For welds longer than 2 or 3 ft, the guide tubes are usually insulated to prevent them from making electrical contact with the sidewalls of the joint.

There are two methods of insulating consumable guide tubes: (*a*) by coating them with flux, and (*b*) by use of insulator rings (available for this specific purpose) spaced 12 to 18 in. apart and held in place by a small button of weld on the guide tube. The flux cover

insulates the tube above the weld so that, if it touches the sidewalls, no electrical contact is made; also, as the steel guide tube melts, the flux cover helps to replenish the flux pool. Insulator rings melt as the guide tube is consumed and become part of the flux.

Dams (also called mold shoes and retaining shoes) are required to hold the molten metal and flux between the parts being welded.

In conventional single-pass electroslag welding of square-groove butt joints, two dams are ordinarily used. They are attached to the welding machine and move vertically as welding proceeds. When a backing bar is employed on one side, with the conventional process, only one dam is needed. With the conventional process, the front dam (nearest the machine) is always required. However, with the consumable-guide-tube system, it is possible to use two backing bars, under which conditions no dams are needed. Backing bars can be left in place when welding is finished, to become a part of the weld, or they can be cut off, as required by the job. A special type of dam is described in Example 369 in the article on Electrogas Welding.

Dams used with the conventional system are always water cooled and are usually made of copper. The principal features of one type of water-cooled dam are shown in Fig. 4 — designs of dams vary considerably. In the setup shown in Fig. 4, the two plates to be welded are aligned to allow a typical 1¼-in. joint opening. The two copper dams close the ends of the joint opening and form the cavity for molten weld metal and flux.

The dams shown in Fig. 4 are constructed from copper plates and are assembled by brazing or welding. This particular design has a center partition, or baffle, containing one or more openings, to improve circulation of the cooling water.

Dams used with the conventional process require brackets or similar devices for attachment to the welding machine arms, so they will slide upward along the joint as welding proceeds (see Fig. 2). When welding long joints (longer than the distance from the bottom of the dams to the top of the horizontal arm), the horizontal portion of the arm must be narrow enough to move vertically within the joint opening.

Dams used with the consumable-guide-tube system remain stationary until they are manually relocated along the joint. Clamps and similar devices have been used to hold them in place, but the most common method is to use wedges inserted under the strongbacks (see Fig. 3). Water-cooled dams of the type shown in Fig. 4 are also used with the consumable-guide-tube system. They are available in standard lengths of 12, 18 and 24 in.

Dams used with the consumable-guide-tube system need not be water cooled, but if they are to be reused, they must be made from massive copper blocks. Because such blocks are expensive and deteriorate rapidly, water-cooled dams are generally recommended. In Example 366 (see page 392), the copper dam was not water cooled.

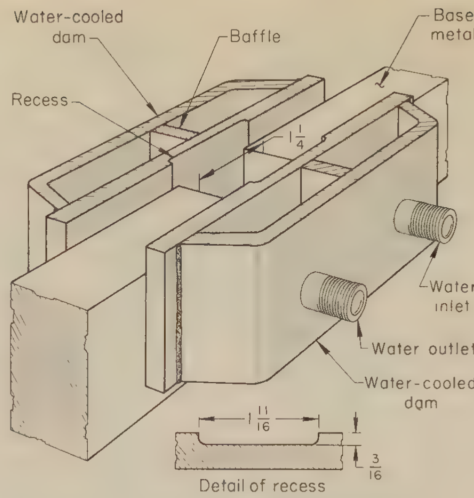


Fig. 4. One type of water-cooled dam

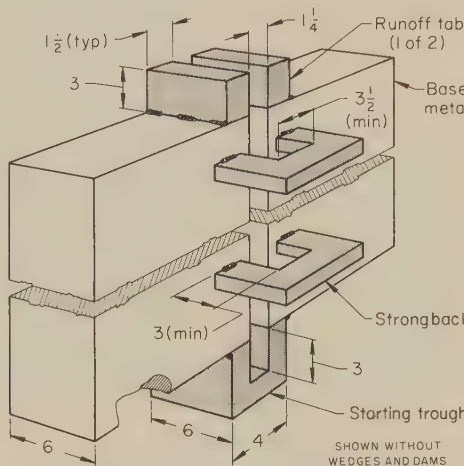


Fig. 5. Two 6-in.-thick plates ready for electroslag welding

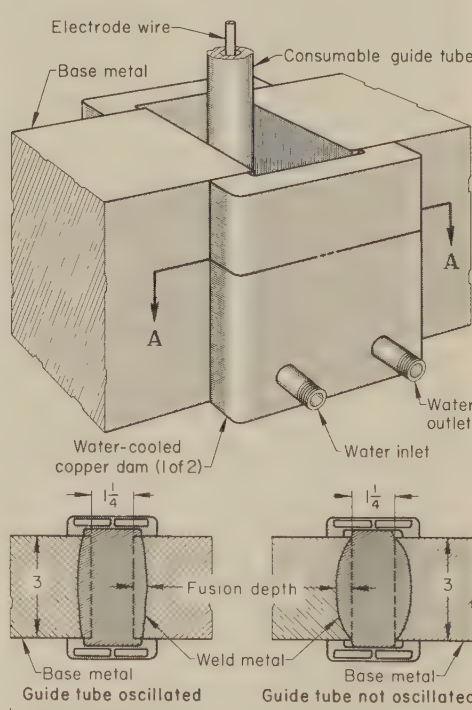


Fig. 6. Setup for consumable-guide-tube electroslag welding of 3-in.-thick plates. Note different depths of fusion obtained with and without guide-tube oscillation.

Wire-Feed Systems. Irrespective of the electroslag system used, the electrode wire must be fed through the wire guide at a pre-established, constant rate. Although wire-feed systems vary in design among manufacturers, they are almost always of the push type. Wire-feed systems are similar to those used for other welding processes that utilize continuously fed consumable electrodes, and are discussed in the articles on Flux-Cored Arc Welding and Gas Metal-Arc Welding, pages 24 and 78, respectively.

Oscillator mechanisms are required when the thickness of the components to be joined exceeds about 2¼ in. per electrode wire. The means of obtaining oscillation varies with the equipment manufacturer. One method utilizes a motor-driven lead screw (see Fig. 1 in the article on Electrogas Welding, page 395). Rack-and-pinion mechanisms also provide oscillation. The mechanism must be capable of being regulated for distance and rate of travel, and also be able to make an adjustable delay at the end of each stroke.

Electrode Wires

Either solid or tubular electrode wires can be used as the filler metal in both systems of electroslag welding.

Solid electrode wires such as are used for gas metal-arc or submerged-arc welding are most often employed. Electrode wires that contain deoxidizers such as those that conform to AWS A5.18-69 are most often used for electroslag welding of low-carbon and medium-carbon steels. For welding alloy steels, it is common practice to choose an electrode wire with alloy content that produces a weld that nearly matches the base metal. The carbon content is usually between 0.07 and 0.19%, irrespective of alloy content.

Tubular electrode wires used for electroslag welding usually contain powdered ferroalloy. The wire is always of low-carbon steel, but the composition of the alloy powder core can be varied to produce a desired composition of weld deposit.

Tubular wire having a core composed entirely, or almost entirely, of flux, such as is used for flux-cored arc welding, is sometimes used for electroslag welding. Flux-cored wires have usually resulted in excessive buildup of flux in the pool (more than 2 in.), and good fusion is impaired.

Size of electrode wire varies from 3/32 to 5/32 in. in diameter. The 3/32-in.-diam size is most often used with the consumable-guide-tube system, because the inside diameter of the guide tubes is often ⅛ in., but consumable guide tubes can be obtained that permit feeding of ⅛-in.-diam wire (see Examples 366 and 367). The same diameter restrictions do not apply in the conventional system, and ⅛-in.-diam wires are most often used. Because they are stiff, wires more than ⅛ in. in diameter sometimes are difficult to feed.

Fluxes

The molten flux is the "slag" that gives the electroslag process its name.

Composition. Fluxes are marketed as proprietary materials; there are no

standard specifications. Fluxes for electroslag welding are usually combinations of oxides of silicon, manganese, aluminum, calcium, magnesium and titanium, with some calcium fluoride always present. The calcium fluoride is added to the basic system to obtain suitable resistivity and fluidity. As the amount of calcium fluoride is increased, viscosity, melting point, and resistivity decrease. Titanium oxide also decreases resistivity; aluminum oxide increases it. Lower resistivity generally results in a lower flux temperature for a given power input.

The ingredients in the various proprietary fluxes vary considerably. The following composition is typical of one that has performed satisfactorily for electroslag welding of low-carbon steel: 35% SiO_2, 40% MnO, 5% Al_2O_3, 7% CaO, 5% CaF_2, 3% FeO, 3% TiO and 1% Na_2O.

Operating Characteristics. A flux for electroslag welding must meet several requirements:

1. It must be sufficiently conductive when molten to carry the welding current from the electrode to the molten weld puddle and to the surfaces of the solid base metal without arcing. With a constant-voltage power supply, the electrode melts off on penetrating only part way through the flux pool. Because the current drawn from a short length of wire has to maintain the temperature of a 2-in.-deep flux pool, a flux of the correct resistivity must be chosen. A flux of high resistance will draw too little current, allowing the pool to cool and the wire to drive too deeply into the molten flux. A flux of low resistance will draw excessive current, raising the temperature of the pool until the process stabilizes with a shorter length of wire immersed. A flux with too little resistance may lead to arcing above the flux pool.
2. Flux viscosity must be in the range between the high viscosity that results in sluggishness and prevents settling of small droplets of molten metal (and also leads to slag inclusions in the weld) and the low viscosity that causes the flux to leak through small crevices between the dams and the work. Viscosity must be low enough to permit a good stirring action in the flux pool, so that heat will be distributed uniformly to all surfaces of the joint. This is especially important in a small flux pool, as in welding relatively thin plates.
3. The flux must have a melting range lower than that of the weld metal. All ingredients in the flux should volatilize slowly. Preferential loss of one ingredient will alter the pool composition and lead to varying results in long welds.
4. The flux must be metallurgically compatible with the alloy being welded. For carbon steel, low-alloy steel, and stainless steel, a basic flux is usually recommended. The same flux and a simple flux composed principally of fluorspar and lime have been used for nickel alloys.
5. The flux should solidify to a slag that is easily removed from the surface of the weld. The commercially available fluxes differ in this characteristic, some being rather difficult to remove. This is seldom a major consideration.

Starting Flux. Specially compounded fluxes that have lower-than-normal resistivity and that are used with higher-than-normal voltage and current can be used for startup, to develop the flux pool and the weld-metal puddle. After startup, welding is done with the regular welding flux. Some fabricators do not use a special startup flux.

Table 1. Typical Conditions for Electroslag Welding With the Consumable-Guide-Tube System

Plate thickness, in.	Number of electrodes	Root opening, in.	Total current, amp	Voltage, v	Oscillation distance, in.	Oscillation speed, ipm
½	One	1	500	34 to 36	0	0
1	One	1	600	37 to 39	0	0
2	One	1	725	38 to 40	0	0
2⅜	One	1¼	750	39 to 41	1¾	20
3	One	1¼	750	39 to 41	2⅜	25
5	One	1¼	750	45 to 47	4⅜	50
5	Two	1¼	1500	40 to 42	1⅛	10
6	Two	1¼	1500	41 to 43	2⅛	25
8	Two	1¼	1500	44 to 46	4⅛	45
10	Two	1¼	1500	47 to 49	6⅛	65
12	Two	1¼	1500	50 to 52	8⅛	85

Workpiece Preparation

Preparation of the joint edges is often much simpler than for other welding processes (see Examples 365 and 367). Plates are usually cut to size by gas cutting and then are ready to weld without further edge preparation. This simple procedure saves considerable time and money compared with preparation by beveling.

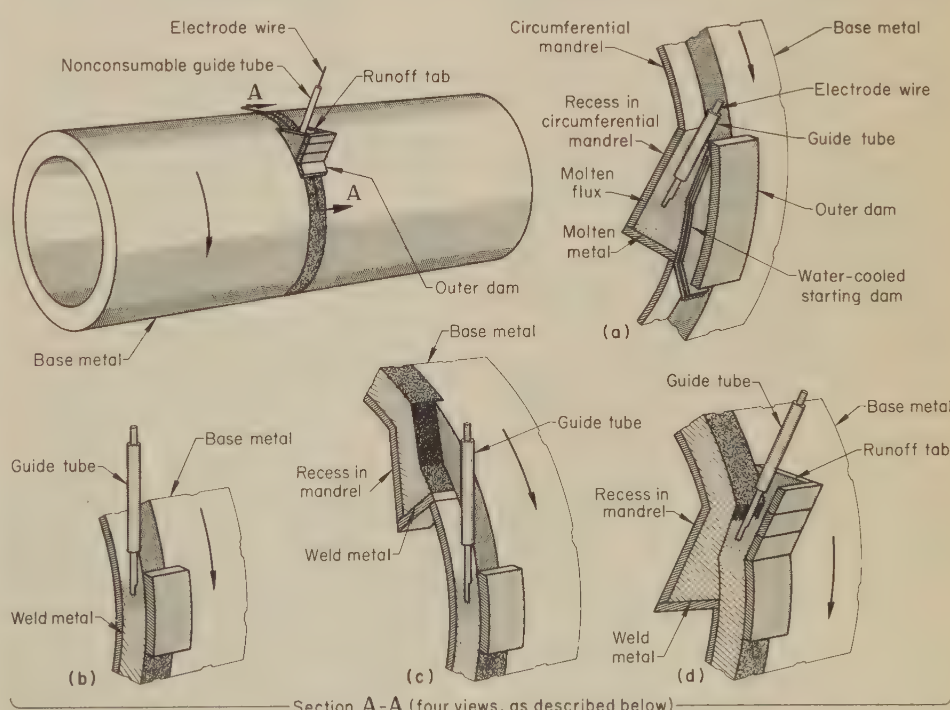
Joint components to be welded are assembled in a vertical position, supported over a starting trough of full plate thickness and about 3 in. deep (see Fig. 5). The starting trough can be made by tack welding together three pieces of scrap steel plate, or it can be a clamp-on starting sump made from copper, which type can be reused many times. The faces of the starting trough must be flush with the outside surfaces of the plates, for proper fit of the dams. The runoff tabs (Fig. 5) are also full plate thickness and about 3 in. deep, so as to bring the weld crater beyond the top of the plates.

Strongbacks. Spacing of the joint opening (usually 1⅛ to 1¼ in.) and alignment of the plates must be maintained. The most common means of accomplishing this is by the use of U-shape restraining plates (strongbacks) welded across the outer face of the joint, as shown in Fig. 5.

For welding by the conventional system, the openings of the strongbacks must be large enough to permit the water-cooled dams to move through them. A space of 3½ by 3 in., as shown in Fig. 5, is usually sufficient.

With the consumable-guide-tube system, dimensions of the strongback are not critical. In this system, the strongbacks serve the additional function of helping to hold the stationary dams in place (see Fig. 3).

The number of strongbacks along a joint depends mostly on the workpieces and the degree of difficulty encountered in maintaining them in position. The ease or difficulty of fit-up will also determine whether strongbacks are needed on both sides of the joint. Strongbacks are commonly located 12 to 18 in. apart, starting about 6 in. from the bottom of the joint and ending not much nearer the top than 6 in.



(a) Setup for beginning the weld, showing recessed internal mandrel, starting dam, and outer dam. (b) Welding the major portion of the circumference, using a mandrel and a contoured outer dam. (c) Approaching the finish of the weld. (d) Completing the weld with the help of runoff tabs and additions to the outer dam.

Fig. 7. Circumferential electroslag welding

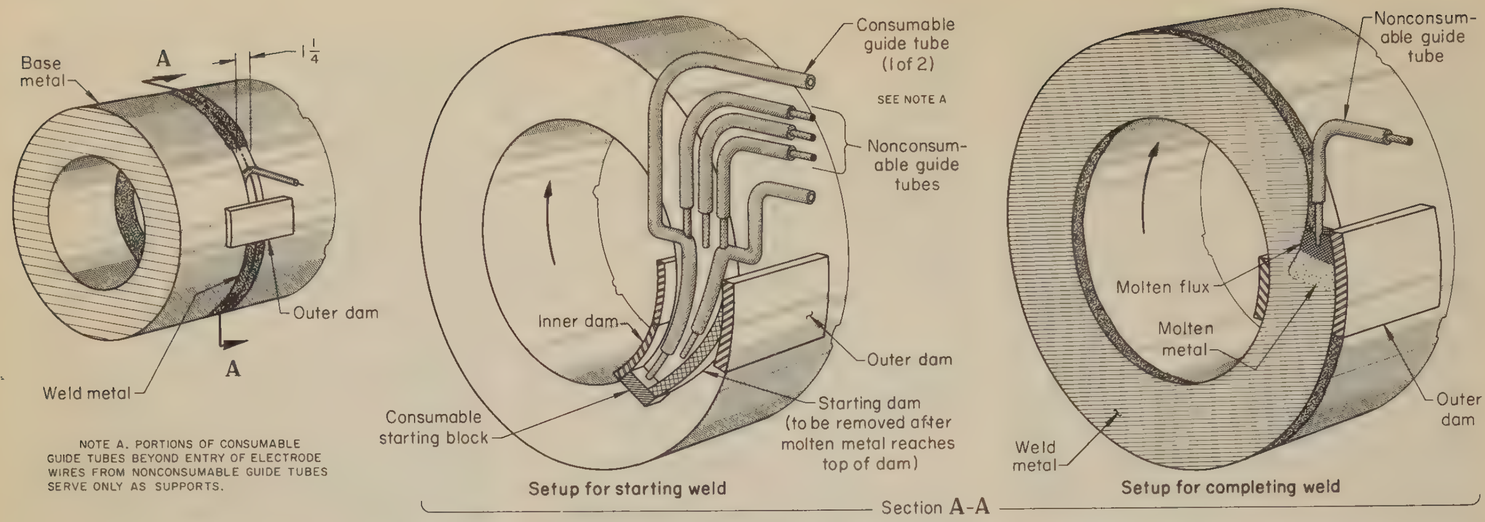


Fig. 8. Electroslag welding of cylindrical sections, using a combination of the conventional and consumable-guide-tube systems. Note setups for starting the weld, obtaining initial contour, and completing the weld.

In some setups, the workpieces are easily positioned and fewer than the normal number of strongbacks are adequate. In other setups, fit-up is difficult and extreme force (applied by power jacks or a crane) may be required to get the workpieces into position, and additional strongbacks must be used. Sometimes, when welding with the consumable-guide-tube system, the placement of the water-cooled dams influences the number and location of strongbacks, because the water-cooled dams depend on the strongbacks to hold them in position.

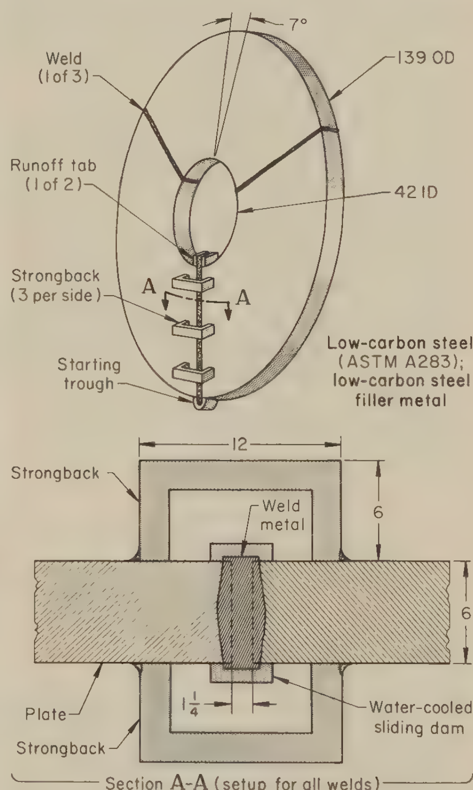
In the conventional system, it is highly desirable to use strongbacks only on the side opposite that from which the electrode wires are fed. If strongbacks are used on both sides, they must be successively removed on the wire-feed side as the welding machine travels up the joint.

Strongbacks are removed after the joint is welded, unless the operation makes it necessary to remove them sooner, as mentioned above. If they have been securely welded, they can be removed by gas cutting at about ¼ in. from the face of the finished joint. If service requirements make it necessary to remove all evidence of the strongback, the remaining ¼ in. should be chipped and ground away. However, strongbacks often are only tack welded along one side and can be broken off with a few sledgehammer blows.

Preheating. Because of the thermal cycle that characterizes electroslag welding, preheating is seldom used. Sometimes, the joints are warmed with a torch to drive off moisture before welding begins. Also, if high-strength steels are welded, preheating may be required. (See the section in this article on Preheating and Postheating, page 390.)

Operating Procedure

In setting up for electroslag welding, the entire welding machine is positioned over or beside the gap between the two workpieces. For welding by the conventional system, the machine is lowered and raised to make certain that the guide tube (or tubes) enters and leaves the joint opening smoothly



Process	Conventional electroslag welding
Joint and weld types	Butt; square groove
Joint preparation	Gas-cut edges
Power supply	Two 750-amp transformer-rectifiers(a)
Electrode wires	Two ⅛-in.-diam low-carbon steel
Number of passes	One
Current, amp (dcrp)	750 per wire; 1500 total
Voltage	50 v
Electrode consumption	25.2 lb per foot
Flux consumption	50 gr per hour
Oscillation	2⅛-in. length of travel at 60 ipm
Preheat	100 F (by gas torch)
Stress relief	1150 ± 25 F, 7 hr
Deposition rate	90 lb per hr (total, two wires)
Setup time (total, 3 joints)(b)	5.2 hr
Welding time per joint	1.15 hr
Postweld trimming time(c)	0.25 hr

(a) Constant-voltage type, 100% duty cycle. (b) Includes positioning welding machine, aligning, and attaching strongbacks. (c) Total, for cutoff of starting troughs, runoff tabs, and strongbacks from all three joints.

Fig. 9. Grinding-mill head that was fabricated by joining three plate sections by electroslag welding (Example 361)

and remains centered in it. The roller guide shown in Fig. 2 provides a means of keeping the machine aligned after the initial adjustments are made. The dams are checked to make sure that they will slide freely. Wire-feed rate, reference voltage, and current are adjusted. Electrode-wire size and required deposition rate must be considered in making the initial settings. If experience with similar applications is not available, the best procedure is to use the data supplied with the particular machine as a starting guide. However, sample welds should be made and tested to ensure that the welding procedure will provide joints having the required properties.

Setup for the consumable-guide-tube system is similar to the above. When the machine is made ready, the guide tube is adjusted so that it extends nearly to the bottom of the joint and does not touch the sidewalls of the workpieces (unless it is well insulated). The dams are then wedged in place.

Startup is almost always done with the aid of a piece of steel wool placed in the starting trough. The electrode is lowered into the starting trough (both systems), and as it touches the steel wool, violent arcing takes place. Flux is added immediately. A large handful is usually sufficient, although the quantity depends on the thickness of the joint. The flux can be a special starting flux. In some plants, the initial flux is placed on top of the steel wool before the current is switched on.

As soon as the flux melts and the violent arcing dies down, more flux is added. The arc is soon extinguished and welding begins. The objective is to have welding proceeding smoothly by the time the flux level rises to the bottom of the joint. To obtain a smoother start, especially if a special starting flux is used, the voltage can be increased and the amperage decreased during startup.

After the arc has been extinguished, welding proceeds continuously until the joint is completed. During welding, some adjustments in current or wire feed may be needed. Welding-current variations of about 30 amp caused by variations in line voltage can be tolerated for periods of not more than about

half a minute, after which the current should be readjusted to correct value.

Flux is added manually as needed to maintain a molten-flux depth of about 1½ to 2 in. Attempts to automate the addition of granulated flux have not been successful, largely because only a small amount is consumed. On the average, about 1 lb of flux is used per 20 lb of weld metal deposited. The amount of flux consumed depends largely on the amount that is lost by leaking out between the dams and the workpiece. Very little is consumed by the process. When welding with the consumable-guide-tube system, some welding engineers prefer flux-covered guide tubes, which automatically help to replenish the flux pool as welding proceeds. Although depth of the pool is not critical, for best welding efficiency, the depth should be kept reasonably uniform and generally should not exceed 2 in. If the flux starts to bubble vigorously, the flux pool is too shallow and flux should be added, and if the surface of the flux pool is entirely quiet, it is too deep.

Although the welding operation for both the conventional and consumable-guide-tube systems is largely automatic, additions of flux, minor adjustments of the machine, and changing of dams, in the consumable-guide-tube system, demand fairly close surveillance.

Typical operating conditions for electroslag welding of plates ranging in thickness from ½ to 12 in., using the consumable-guide-tube system, are presented in Table 1.

Oscillation. Thickness of the work metal is the major factor in determining whether or not the guide tubes (and electrodes) should be oscillated during welding. When work-metal thickness is less than about 2¼ in., oscillation is not usually required, although it is sometimes used for work metal as thin as 1½ in. Better uniformity of heat penetration is obtained when the electrode is oscillated, even in welding thin plates. Because the water-cooled copper dams are efficient heat sinks, when the electrode remains stationary in the center of the joint opening and midway between the two sides, heat penetration is considerably greater at the center of the joint than at the edges. Oscillation will greatly lessen this nonuniform distribution of heat; a dwell time of 1 sec or more at each end of the stroke will compensate for the heat loss due to the water-cooled dams. Figure 6 shows the effect of oscillation on depth of fusion in welding 3-in.-thick plates. A base-metal thickness of 3 in. generally is considered excessive for welding with one electrode wire, and without oscillation. As shown at the lower right in Fig. 6, there is little depth of fusion at the four corners adjacent to the dams if oscillation is not used.

Sometimes the fusion is deep on one side of the joint and very shallow on the opposite side. This may be caused by an excessive amount of flux or by the electrode not being centered between the joint walls, thereby providing a shorter path for the current flow to a joint sidewall instead of down to the molten weld metal. Also, when current flow is to one sidewall, the flux pool near the opposite sidewall will cool, which can result in slag inclusions in the weld metal. Oscillation will decrease this effect and promote more even depth of fusion.

The oscillator mechanism moves the guide tube back and forth within the joint opening. The length of travel can be varied, but is usually set so that the guide tube stops at each side, about ⅜ to ½ in. from the dam. The oscillation distance depends on the thickness of the plates and the number of electrode wires. For a particular plate thickness, oscillation distance is considerably less for two wires than for one (compare the values for 5-in.-thick plate in Table 1). Usually, delay (dwell time) is 1 to 7 sec before the direction of travel is reversed. This delay helps to keep the flux pool at a uniform temperature. Oscillation speed varies with oscillation distance, as shown in Table 1.

Number of Electrode Wires. One wire with no oscillation is recommended for work-metal thicknesses of ½ to 2⅜ in., one wire with oscillation for thicknesses of 2⅜ to 5 in., and two wires with oscillation for thicknesses of 5 to 12 in. Some welding engineers regard the 2⅜-in. thickness as too great for welding without oscillation. Also, it is sometimes preferable to use three electrode wires with oscillation as work-metal thickness approaches 12 in. In some applications, particularly for the consumable-guide-tube system, the use of more electrode wires can replace oscillation (see Example 367). In one application, 22-in.-thick plates were welded using six wires not oscillated.

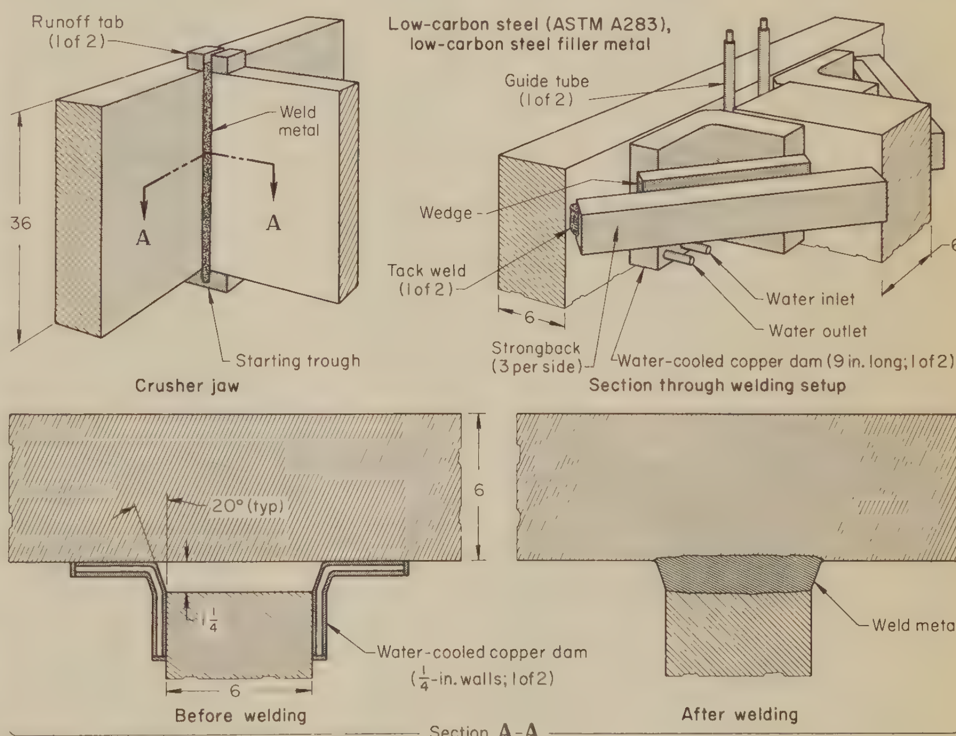
Control of Vertical Travel. Best results are obtained by maintaining close control of vertical travel, when the conventional electroslag system is used, so as to keep the length of wire in the flux pool constant. Even though the equipment may provide for automatic control of vertical travel, the rate of travel requires periodic adjustment during welding, particularly when long welds are being made.

With the consumable-guide-tube system there is no vertical travel, but electrode-feed rate (which controls current) must be closely controlled.

Circumferential Welding

Circumferential welds for joining sections of thick-wall pipe or pressure vessels can be made efficiently by the electroslag process. The methods used differ considerably from those used in welding straight vertical joints.

One method is essentially the same as that described in the article on Electrogas Welding, page 395 (see also Fig. 7 in that article). In this method,



Joint type	T, with square-groove weld	Number of passes	One
Joint preparation	Gas-cut edges	Current (dcrp)	750 amp per wire; 1500 amp total
Fixtures	Strongbacks; wedges	Voltage	41 to 43 v
Power supply	Two 750-amp transformer-rectifiers(a)	Preheat	150 F
Electrode wires	Two; 3/32-in.-diam low-carbon steel(b)	Stress relief	1150 ± 25 F, 6 hr
Guide tubes	Two; ⅝-in. OD, ⅛-in. ID(c)	Welding speed	0.72 ipm

(a) Constant-voltage type, 100% duty cycle. (b) Wires supplied from 750-lb reels. (c) Low-carbon steel.

The two-piece weldment shown replaced a single-piece cast jaw, at a cost saving. Joint configuration was better suited to electroslag welding by the consumable-guide-tube system than by the conventional system.

Fig. 10. T-section of a rock-crusher jaw that was electroslag welded, using a starting trough, runoff tabs, strongback fixtures, and specially shaped water-cooled dams, as shown (Example 362)

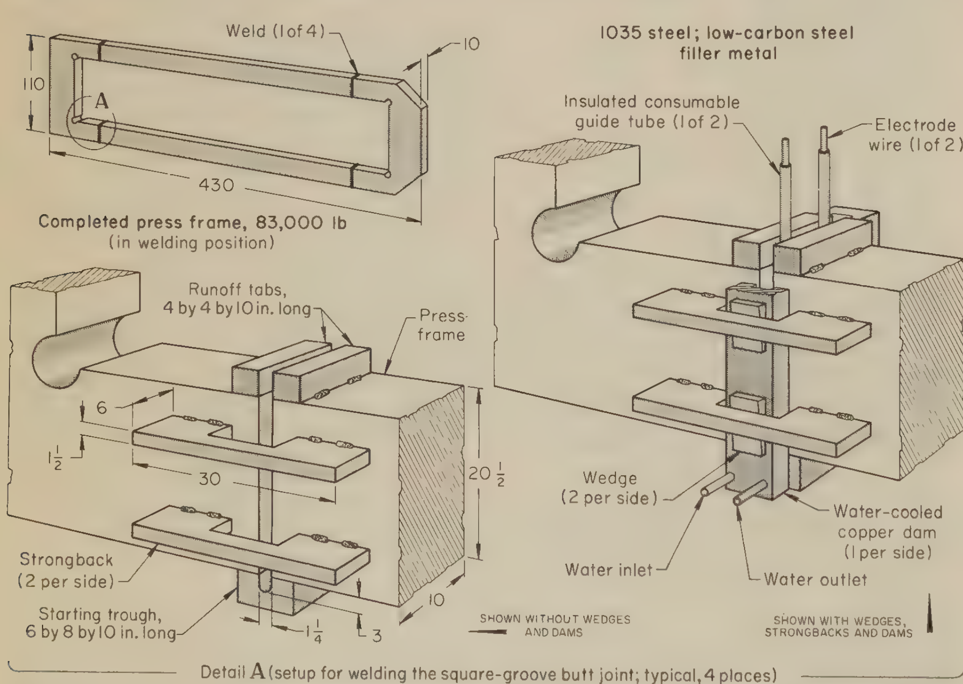
the dams fit the curvature of the workpiece, and they, as well as the other welding equipment, remain stationary as the workpiece is rotated. A major disadvantage of this method is that the weld cannot be completed by electroslag welding. After all but about 18 in. of the circumference has been welded, the electroslag equipment is removed and the weld is completed by another process, such as shielded metal-arc welding.

Other methods involve rotating the work past a stationary welding head, using special techniques for starting and finishing the joint. A dam within the cylinder must be used. This dam may be a single mandrel or several separate dams tacked or bolted in position in "leapfrog" progression as the weld advances.

One method for starting and closing a circumferential weld is as follows. Welding is started on a simple dam that is tacked in place on the inside of the cylinder. Preparation for closing is made when welding is half completed, by cutting away the starting dam and gouging out the first weld metal deposited along a predetermined surface that is tangent to the inside diameter. Tapered finishing tabs are tacked in place outside the joint at this location, so that the weld puddle can be brought to the surface of the cylinder as the joint is completed.

A method and apparatus covered by U. S. Patent 3,433,926 is sometimes used to provide the same kind of contoured start and finish as described above. The weld is started by use of a mandrel having a recess contoured as shown in Fig. 7(a) (which serves as the inner dam), a specially shaped water-cooled starting dam, and another dam shaped to the outer contour of the workpiece. Welding begins by positioning the guide tube as shown in Fig. 7(a) and filling the recessed area in the mandrel with weld metal. The shape of the water-cooled starting dam causes the weld to have a taper at the bottom. After the recessed area is filled and has solidified, the water-cooled dam is removed, as welding continues. As the workpiece rotates in the direction shown in Fig. 7(b), the flux and weld metal are retained by the mandrel and the contoured outer dam. As the weld nears completion, runoff tabs are attached, and these, with the aid of the taper at the beginning of the weld and additions to the outer dam, permit completion of the weld as shown in Fig. 7(d). The mandrel is then removed, and the excess metal at the start and finish is cut off. This method is not efficient for wall thicknesses of more than about 4 in.

A more elaborate method for circumferential welding is shown in Fig. 8. A starting dam is used to mold the initial weld into the contour needed to complete the weld. Inner and outer dams are also used. The inner dam can be a mandrel, or short dam segments can be used by "leapfrogging". The outer dam is usually fastened to the welding machine and remains stationary as the workpiece rotates.



Joint type	Butt	Current (dcrp)	700 amp per wire; 1400 amp total
Weld type	Square groove	Voltage	52 v
Joint preparation	Gas-cut edges	Oscillation:	
Fixtures	Strongbacks; wedges	Speed	122 ipm
Power supply	Two 750-amp transformer-rectifiers	Travel	6 in.
Electrode wires	Two 3/32-in.-diam(a)	Dwell time	2 sec(c)
Guide tubes	Two 5/8-in.-diam(b)	Frequency	20 cycles per minute
Flux depth	1½ in.	Postheat	Stress relief

(a) Composition: 0.11 C, 1.20 Mn, 0.45 Si, 0.020 S, 0.020 P. (b) Insulated with ceramic ferrules or glass fiber. (c) Within ½ in. from each dam.

Fig. 11. Setup for consumable-guide-tube electroslag welding of four sections of 10-in.-thick plate for fabrication of a press frame (Example 363)

The significant feature of this method is the guide-tube arrangement. As shown in Fig. 8 (center), at the time welding starts, there are five guide tubes, three nonconsumable and two consumable, but no more than three electrode wires are fed at any one time. The two consumable guide tubes serve as extensions of the corresponding nonconsumable guide tubes, so as to lead the electrode wires in the latter down into the pocket provided by the starting dam. The consumable guide tubes gradually melt off, until they are consumed, and then welding continues from the three electrode wires as they emerge from the nonconsumable guide tubes. The supports for the consumable guide tubes are then removed. At this point, rotation of the workpiece begins and the starting dam is removed. Welding continues in a normal manner, electrode wire being supplied through the three nonconsumable guide tubes, until the starting point is approached. Then, the two innermost guide tubes are removed successively, as the depth of the joint tapers down (Fig. 8, right). The joint is finished with only one electrode wire being fed. A small crater that can usually be blended in without runoff tabs is left.

Preheating and Postheating

The thermal cycle developed by electroslag welding is different from that resulting from arc welding. The temperature of the flux pool, normally from 3000 to 3500 F, is much lower than the temperature of a welding arc, but the total amount of heat for electroslag welding is much greater than for arc welding. As a result, a larger area is heated, but more slowly. Thus, in effect, the process incorporates a preheating operation.

Because a great amount of heat is imparted to the entire area around the weld, cooling is relatively slow and postheating is usually not required. However, postweld heat treating is often used to obtain specific properties.

Production Examples

Of the seven examples that follow, two describe electroslag welding by the conventional system; the others deal with electroslag welding by the consumable-guide-tube system.

Because electroslag welding is capable of extremely high deposition rates, it is generally less costly than other welding processes for joints in massive parts in which hundreds of pounds of filler metal must be deposited. In some of the applications that follow, weldments were comprised of several castings, or of various combinations of castings, wrought shapes, and forgings, that would have been impractical to fabricate by any process other than electroslag welding. The first three examples describe applications in which a large weldment was used instead of a single casting.

Example 361. Use of a Three-Piece Weldment To Reduce Cost and Lead Time (Fig. 9)

As originally designed, the 139-in.-diam 34-ton grinding-mill head shown in Fig. 9 was a single ductile iron casting. Changing

to a weldment comprised of three sections of 6-in.-thick low-carbon steel plate, joined by electroslag welding, reduced production cost by 50% and lead time by 17 weeks.

The three plate sections were held in alignment by strongbacks as shown in Fig. 9. The strongbacks were removed in succession as required by vertical movement of the equipment. The assembly was rotated so that each joint was in the vertical position during welding.

Welding was initiated by placing granulated flux in the well that was formed by the starting trough and two 9-in.-long water-cooled copper dams, and advancing two ⅛-in.-diam electrode wires (from a welding head) into the flux, melting the flux and forming the puddle of molten weld metal. Welding was done in a single pass with the welding head oscillating the electrodes across the length of the gap between the plates, to within ½ in. of the dam on each side of the joint. A dwell of 1 sec at each side was included in the oscillation cycle.

Under the welding conditions given in the table with Fig. 9, void-free welds, with minimum shrinkage, were obtained. Joint shrinkage was about 1⁄16 in., compared with the ⅜-in. shrinkage normally obtained when using submerged-arc welding. Filler-metal deposition rate was 90 lb per hour, from two wires, at a vertical-travel rate of 0.72 in. per minute. After welding, all weld reinforcements were ground flush and welds were subjected to 100% radiographic and ultrasonic inspection.

The same process was used for making other grinding-mill heads from plates up to 12 in. thick.

Example 362. Replacement of a Casting by a Weldment To Reduce Cost and Lead Time (Fig. 10)

Jaws for rock crushers were originally made as ductile iron castings, but to reduce cost and lead time, the castings were replaced by weldments comprised of two 6-in.-thick plates of ASTM A283 low-carbon steel. Electroslag welding, using the consumable-guide-tube system and the conditions listed in the table with Fig. 10, was employed. The welded T-section of a crusher jaw is shown at upper left in Fig. 10.

The joint edges were prepared by gas cutting, and plates were aligned and fastened in position by tack welded strongbacks and wedges, as shown at upper right in Fig. 10. The assembly was preheated to approximately 150 F with torches to ensure that the joint was dry. At first, because of the joint configuration, solid copper dams were used (no water cooling), but these dams became overheated and shaped water-cooled dams were therefore substituted. The water-cooled dams were 9 in. long, and were made by brazing together ¼-in. formed copper plates. A plan view of a cross section of the joint area and dams is shown at the lower left in Fig. 10.

Two consumable guide tubes, inserted at the top of the joint (Fig. 10, upper right) and extending down its entire length, carried the electrode wires into the starting trough. The water-cooled dams were "leap-frogged" as required during welding. A cross section of the welded joint is shown at the lower right in Fig. 10.

After welding, the strongbacks, starting trough, and runoff tabs were removed and the weldment was stress relieved at 1125 to 1175 F for 6 hr. After stress relief, the weldment was inspected ultrasonically.

Conditions for welding the joint are given in the table with Fig. 10. This joint is typical of those that are better suited to welding by the consumable-guide-tube system than by the conventional system.

Example 363. Electroslag Welding an 83,000-Lb Press Frame From Four Plate Sections (Fig. 11)

Because the press frame shown in Fig. 11 (upper left) was too large for production as a single piece by casting or by cutting from a large plate, it was fabricated by joining four sections of 10-in.-thick medium-carbon steel (1035) plate by consumable-guide-tube electroslag welding.

The components of the frame were prepared by gas cutting, and each joint was aligned (leaving a root opening of 1¼ in.) and held in position by means of strongbacks tack welded to both sides of the joint. Starting troughs and runoff tabs were welded to the bottoms and tops of the four joints. A typical setup is shown at the lower left in Fig. 11. The workpiece was then turned on edge, as shown in Fig. 11, and water-cooled copper dams (about 28 in. long) were wedged in position at the two joints on the lower side (as made ready for welding) of the frame. Starting flux was placed in the starting trough, and two consumable guide tubes were inserted into the 1¼-in. gap between the frame sections (Fig. 11, right). The guide tubes were insulated with ceramic ferrules or glass fiber to prevent electrical contact with the sidewalls of the joint. During welding, the guide tubes were oscillated along the width of the joint to within about ½ in. of the copper dams. The dwell time at each end was 2 sec. After the first joint had been completed, the guide tubes were replaced and the welding head was moved to the second joint, which was welded in the same manner. Welding conditions are given with Fig. 11.

After completion of the first two welds, the workpiece was turned 180° and the remaining two welds were made by the same procedure. The completed weldment was stress relieved. Quality was verified by ultrasonic inspection.

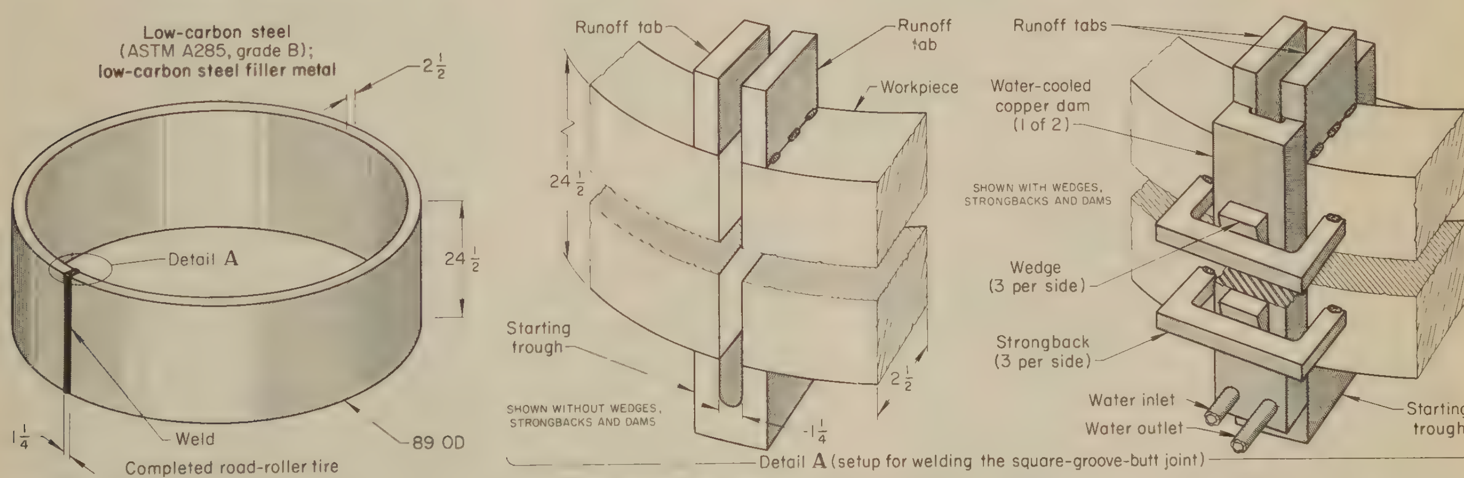
Five press frames were made by the procedure described.

Electroslag Welding vs Other Welding Processes

Deposition rates are higher for electroslag welding than for any other welding process — at least 25 to 50% higher than for submerged-arc welding, which is usually the closest to electroslag welding in deposition rate.

In some applications, electroslag welding is closely competitive with electrogas welding. Equipment used and principles of operation are similar. The range of work-metal thickness is much narrower for electrogas welding (⅜ to 4 in.) than for electroslag welding, and deposition rates are much lower. Consequently, heat input is less and cooling rate is higher in electrogas welding. Sometimes, these characteristics are advantageous (see Example 369 on page 400, in "Electrogas Welding").

Electroslag welding is not suitable for welding complex structures in which the joints are short or interrupted, or in which the time required to align the joint for welding in the vertical direction would be too great. In the next example, electroslag welding was chosen because it eliminated a rerolling operation; in Examples 365, 366 and 367, it replaced a slower process.



Conditions for Welding 2½-In.-Thick Tire Shown

Fixtures	Strongbacks; wedges
Power supply	750-amp transformer-rectifier(a)
Electrode wire	3⁄32-in.-diam low-carbon steel
Guide tube	⅝-in.-OD, ⅛-in.-ID 1010 steel
Current and voltage	750 amp, dcrp; 39 to 41 v
Arc time	0.32 hr
Filler-metal consumption	10.55 lb per foot(b)
Welding speed	0.79 ipm

(a) Constant-voltage type, 100% duty cycle. (b) Including guide tube.

Plate thickness, in.	Number of wires	Root opening, in.	Current, amp	Voltage, v	Vertical travel Speed, ipm	Vertical travel Time, min/ft
Conditions for Welding Tires ½ to 6 In. Thick						
½	1	1	500	34 to 36	1.6	10
1	1	1	600	37 to 39	1.2	10
1½	1	1	650	37 to 39	1.1	11
2	1	1	725	38 to 40	0.99	12
2½	1	1¼	750	39 to 41	0.79	15
6	2	1¼	1500	41 to 43	0.72	17

Fig. 12. Road-roller tire, three-roll formed from steel plate of various thicknesses, with a longitudinal square-groove butt joint that was welded by the consumable-guide-tube electroslag process using the setup shown, and under the conditions given in table (Example 364)

Example 364. Use of Electroslag Welding To Eliminate Rerolling of an 89-In.-Diam Road-Roller Tire (Fig. 12)

Road-roller tires (Fig. 12, left) that had been three-roll formed from 2½-in.-thick ASTM A285, grade B, plate were originally welded by the submerged-arc process and rerolled to shape after welding. By changing to the consumable-guide-tube system of electroslag welding, rerolling was eliminated, because the low weld shrinkage (1/16 in. to 5/64 in.) obtained with this process resulted in less work-metal distortion. As a result, the over-all cost of fabrication was reduced, despite the higher cost of welding.

Before welding, the steel plate, gas cut to a width of 24½ in. and approximately 272 in. long, was rolled to an 89-in.-OD cylinder, leaving a root opening of 1¼ in. (Fig. 12, center), which was maintained by strongbacks tack welded to the plates on both sides of the joint at intervals of 8 in. Water-cooled copper dams, extending from the sump of the starting trough to the runoff tabs, were wedged in position against the joint (Fig. 12, right). The guide tube and electrode wire were inserted through the top of the joint. Welding was done with a single electrode wire, without oscillation, under the conditions given in the left half of the table with Fig. 12. No preheating or postweld heat treatment was required. After welding, the outside diameter of the tire was machined to a surface finish of 125 micro-in.

The same procedure was used for welding tires 32 to 84 in. in inside diameter and ½ to 6 in. in wall thickness. Typical welding conditions for this range of plate thicknesses are given in the right half of the table with Fig. 12.

Example 365. Change From Submerged-Arc to Electroslag Welding for Fabricating 7-In.-Wall Pressure Vessels (Fig. 13)

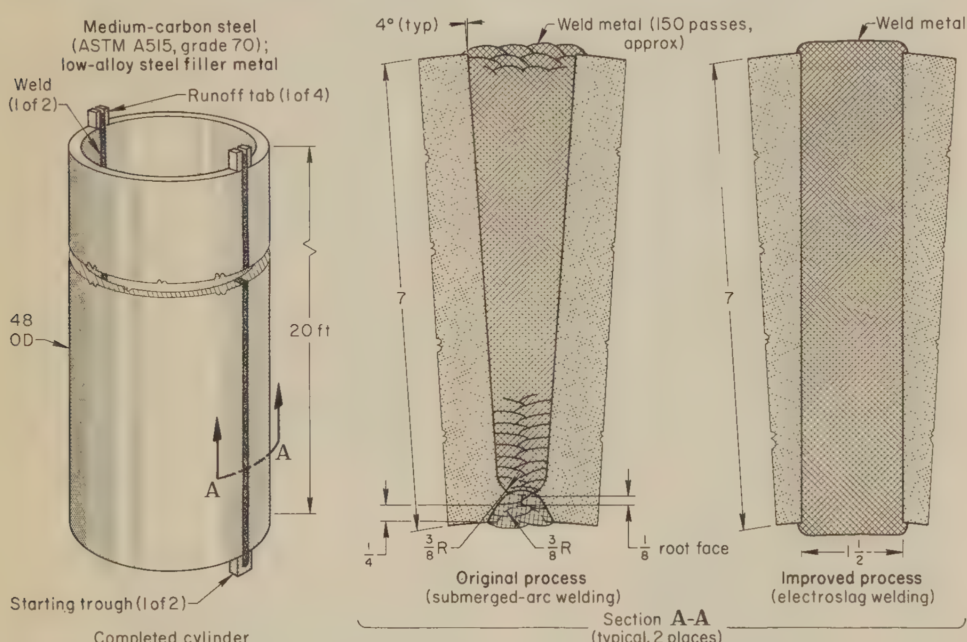
The 48-in.-OD pressure vessel shown in Fig. 13 was fabricated by welding two halves of cylinders rolled from 20-ft-long, 7-in.-thick ASTM A515, grade 70, plate. Originally, the two longitudinal seams of the vessel were welded by the submerged-arc process; later, the conventional electroslag process was adopted, with considerable saving in welding time and improvement in the quality of the weld. Welding conditions for both processes are given in the table with Fig. 13.

For submerged-arc welding, the joints were machined to the double-U-groove shape shown in the middle view in Fig. 13. The large outside groove was welded first and then the inside of the joint was back gouged to sound metal and welded. Using two 5/32-in.-diam electrodes in tandem, about 150 beads were deposited at a rate of 25 to 30 lb per hour. The average welding time per seam was 44 hr.

For the conventional system of electroslag welding, joints were prepared by gas cutting the plate edges to form a square groove with a root opening of 1½ in. (Fig. 13, right), which was maintained by strongbacks tack welded to the walls of the vessel on both sides of the joints. Starting troughs and runoff tabs were attached to the joints, and the vessel was mounted vertically on a positioner table and leveled. Welding was done in a single pass with two 1/8-in.-diam electrode wires, which were oscillated across the joint between two sliding water-cooled copper dams. The copper dams, welding head and controls were mounted on an elevator platform that moved upward along the joint as welding progressed. The strongbacks were progressively removed during welding to allow the dams to move vertically with the level of the rising weld and flux puddle. Welding time per joint was 6½ hr, at a deposition rate of 70 lb per hour. An additional saving in time resulted from there being no need for interpass cleaning, which was required in submerged-arc welding.

The electroslag process produced welds that, under radiographic inspection, were nearly free of voids and slag inclusions, and required no grinding or repair. In contrast, the submerged-arc welded joints had many voids and slag inclusions that necessitated rework. For submerged-arc welded vessels, the rework rate was generally 4 to 6% and occasionally as high as 10 to 15%, whereas for the electroslag welded vessels it never exceeded 2%.

The electroslag welding procedure described above was also applied successfully to similar pressure vessels made from alloy steel (ASTM A387, grades C and D).



Item	Submerged-arc welding	Electroslag welding
Joint type	Butt	Butt
Weld type	Double-U groove	Square groove
Joint preparation	Machined edges	Gas-cut edges
Fixtures	None(a)	Strongbacks; wedges
Power supply	750-amp motor-generator	Two 1000-amp transformers(b)
Electrode wire	Two 5/32-in.-diam EH14	Two 1/8-in.-diam low-carbon steel (Mn-Mo)
Flux	F61(c)	Proprietary(d)
Welding position	Flat (work axis horizontal)	Flat (work axis vertical)
Number of passes	About 150	One
Current, amp	600 to 700, dcrp	650 to 700, ac, per wire
Voltage, v	30 to 31	45 to 48
Deposition rate, lb per hour	25 to 30	70
Electrode stickout, in.	...	2 to 3
Electrode separation, in.	...	2 to 2¾
Oscillation speed, ips	...	½
Dwell time, sec	...	5 to 7
Preheat	250 F min	None
Postheat	...	(e)
Welding speed, ipm	16 to 18	...
Welding time (per seam), hr	44	6½

(a) Joints tack welded initially. (b) Variable output; drooping to constant voltage characteristics. (c) Neutral, fused; mesh size 20×200. (d) Composed of SiO_2, MnO, CaO, CaF_2; quantity used was one twentieth of the weight of metal deposited. (e) Normalized at 1650 F, 1 hr per inch of cross section, for grain refinement; stress relieved at 1150 F, 1 hr per inch of cross section.

Fig. 13. Cylindrical pressure vessel that was fabricated by roll forming two halves and welding them by the submerged-arc (original) and conventional electroslag (improved) processes, using two different joint designs, as shown (Example 365)

Example 366. Change From Flux-Cored Arc to Electroslag Welding for Trunnion Shoes (Fig. 14)

The dam-gate trunnion shoe shown at the upper left in Fig. 14 was fabricated by joining two 2⅝-in.-thick pin plates to a 5-in.-thick base plate. Originally, the plates were welded by the flux-cored arc process, which was later replaced by the consumable-guide-tube system of electroslag welding. Conditions for both processes are given in the table accompanying Fig. 14.

For welding by the flux-cored arc process, a double-bevel corner joint was used, as shown at the lower left in Fig. 14. The plates, which were preheated to a minimum temperature of 225 F, were welded in about 96 passes (48 per joint) using carbon dioxide for shielding. The change to the consumable-guide-tube system of electroslag welding simplified joint design (Fig. 14, lower right) and reduced the time for joint preparation. Preheating was eliminated and welding time per weldment (two joints) was reduced by about half. In addition, weld shrinkage was low and this improved dimensional control, which in turn permitted the pin plates to be surface ground to final size prior to assembly and also helped to hold the spacing between these plates to within 1/32 in. during welding and stress relieving. As a result, machining time per weldment was reduced by 20 hr. Changing to electroslag welding resulted in a total time saving of approximately 32 hr per weldment, or a cost saving of about $23,000 for 90 weldments.

The sequence of operations for welding by the electroslag process was as follows:

1 Fit and tack weld pin plates to the base plate using braces (Fig. 14, upper right).
2 Fit and tack weld starting troughs and runoff tabs.
3 Position the welding head over the joint and center the guide tubes in the joint opening.
4 Position and clamp inner and outer solid copper dams (see Fig. 14, upper right).
5 Add starting flux and weld one joint.
6 Weld the second joint immediately.
7 Remove copper dams and cut off starting troughs and runoff tabs.

8 Stress relieve weldment.
9 Remove braces.
10 Machine.

The first two weldments (four joints) were inspected by radiographic and ultrasonic methods. This inspection served to qualify the process and the operator, and to correlate the two inspection methods. Subsequently, weldments were inspected by ultrasonic testing only.

Slag inclusions occurred in the weld metal of the first two weldments. The two joints of each weldment had been welded simultaneously, which is not an unusual practice. However, when the other weldments were welded one joint at a time, no slag inclusions were encountered. The cause of the slag inclusions was never definitely determined.

Example 367. Electroslag Welding Instead of Gas Metal-Arc Welding for a 7⅜-In.-Wall Cylinder (Fig. 15)

The 37½-in.-diam cylindrical shell shown at the upper left in Fig. 15 was fabricated by welding the gas-cut ends of a formed low-carbon steel (ASTM A113) plate that was approximately 140 in. long, 48 in. wide and 7⅜ in. thick. Originally, the seam was welded by the gas metal-arc process, but later the consumable-guide-tube electroslag process was adopted, at a considerable saving in fabrication time. Welding conditions for both processes are included in the table accompanying Fig. 15.

With the gas metal-arc process, a double-V-groove butt joint (Fig. 15, lower left) was welded in the flat position, using 148 to 175 passes. The sequence of operations was as follows:

1 Manually gas cut plate to size, with the edges for the joint beveled as shown at the lower left in Fig. 15.
2 Clean joint areas.
3 Heat plate and roll form into a cylinder.
4 Reroll cylinder to roundness, and tack weld internal braces to hold it in shape.
5 Preheat cylinder to 250 to 350 F.
6 Weld inside of longitudinal seam in 72 to 85 passes, depending on fit-up.
7 Back gouge the weld to sound metal.
8 Weld outer surface of longitudinal seam in 76 to 90 passes.

The change to electroslag welding permitted a square-groove butt joint (Fig. 15, lower right) to be used. Plate preparation was therefore simplified. In addition, the method of gas cutting was changed from manual to automatic, to reduce the cost of production still further.

The sequence of operations for plate preparation and electroslag welding was as follows:

1 Gas cut plate with an automatic cutting torch.
2 Clean joint area.
3 Heat plate and roll form into a cylinder.
4 Reroll cylinder to roundness, and tack weld strongbacks to maintain root opening of 1⅛ to 1¼.
5 Position cylinder vertically and attach starting trough and runoff tabs.
6 Wedge solid copper dams (2 by 4 by 60 in. long) behind the strongbacks.
7 Position three consumable guide tubes between the edges of the joint (Fig. 15, upper right).
8 Weld in a single, continuous pass.
9 Remove dams, starting trough and runoff tabs.

The joint after electroslag welding is shown in Fig. 15 (lower right). In addition to the time saved in joint preparation, the change to the electroslag process reduced welding time by 32.4 hr (more than 80%) and eliminated preheating.

Welds were examined radiographically in developing the welding procedure. Once the procedure was established, magnetic-particle inspection was used.

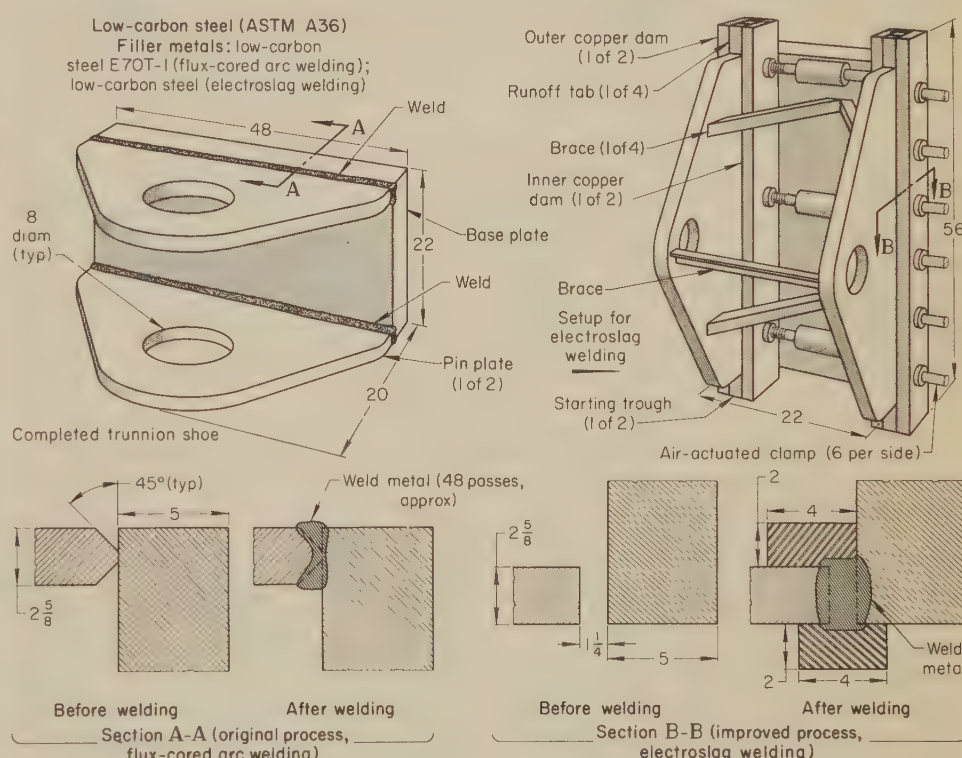
Conventional System vs Consumable-Guide-Tube System

Under most conditions, conventional and consumable-guide-tube electroslag welding give equal results at about the same speed. Factors that influence the choice of system are generally related to the length of joint to be welded, the shape of the joint, the number of pieces to be welded, and the cost of capital equipment.

Length of Joint. Joints up to 20 ft long are welded regularly by the conventional system of electroslag welding. The only limitation on length of joint is the scaffolding or other auxiliary equipment required for controlled vertical travel of the welding machine.

Joints up to 20 ft long have also been successfully welded by the consumable-guide-tube system. Maximum length depends in part on work-metal thickness. If the thickness is no more than about 2⅜ in., longer joints can be welded, with acceptable results, using one electrode wire and one guide tube without oscillation. In general, for welding long joints in thick sections, more than one electrode wire, or oscillation, or both, are required, but it is better to increase the number of electrode wires than to use fewer electrode wires and oscillation. (In Example 367, three wires were used to weld joints 7⅜ in. wide by 48 in. long.) When multiple electrode wires and oscillation are used, guide tubes must be bridged together by welding (not brazing). Maintaining alignment of the guide tubes in the joint opening becomes more difficult as their length increases. Control difficulties become even greater when oscillation is used.

Joint Configuration. For welding square-groove butt joints (the most common type), the two electroslag welding systems are equally suitable. For other types of joints, however, one system is often preferred. For example, if the joint to be welded is curved in the vertical plane, or if it contains some other type of irregularity that prevents a straight guide tube from extending the full length of the joint, electroslag welding may be restricted to the conventional system, although consumable guide tubes can be bent to conform to some configurations. Welding of a T-joint such as described in Example 362 would be difficult, if not impossible, by the conventional system.

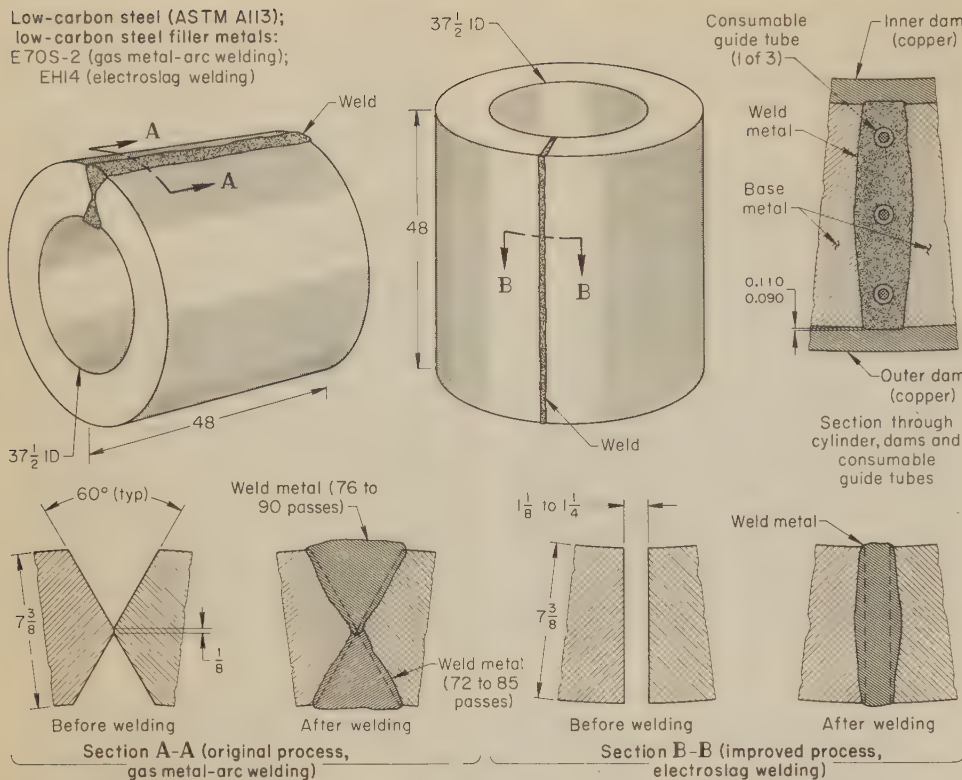


Item	Flux-cored arc welding	Electroslag welding
Joint type	Corner	Corner
Weld type	Double-bevel groove	Square groove
Power supply	...	Two 1200-amp transformer-rectifiers(a)
Electrode wire	⅛-in.-diam E70T-1	Two ⅛-in.-diam low-carbon steel(b)
Guide tube	...	⅝-in.-OD, ³⁄₁₆-in.-ID low-carbon steel(c)
Shielding gas	Carbon dioxide	...
Flux consumption	...	0.10 lb per foot
Welding position	Flat	...
Number of passes	Up to 48 per joint	One
Current (dcrp), amp	500	725 per wire; 1450 total
Voltage, v	30 to 32	38 to 40
Electrode-feed rate, ipm	...	120 to 132
Preheat	225 F min	None
Postweld heat treatment	Heated at 100 F per hr to 1100 F; held 6 hr; cooled at 50 F per hr	Heated at 100 F per hr to 1100 F; held 6 hr; cooled at 50 F per hr
Welding speed, ipm	10 to 12	0.50

(a) Constant-voltage type. (b) Silicon deoxidized. (c) ¹⁄₁₆-in. flux coating.

The consumable-guide-tube electroslag process replaced the flux-cored arc process with a total saving in fabricating time amounting to about 32 hr per weldment.

Fig. 14. Dam-gate trunnion shoe that was fabricated by welding by the flux-cored arc and consumable-guide-tube electroslag processes, with joint design for both processes and setup for electroslag welding (Example 366)



Item	Gas metal-arc welding	Electroslag welding
Joint type	Butt	Butt
Weld type	Double-V groove	Square groove(a)
Power supply	750-amp transformer-rectifier	Two 1200-amp transformer-rectifiers
Electrode wires	5/64-in.-diam E70S-2	Three 1/8-in.-diam EH14
Shielding gas	Carbon dioxide	None
Flux	None	Proprietary
Welding position	Flat	...
Number of passes	148 to 175	One
Current (dcrp), amp	375 to 425	1850 total
Voltage, v	34 to 38	38 to 40
Preheat temperature, F	250 to 350	None
Welding time, hr	39.4	7

(a) 1⅛ to 1¼-in. root opening

Fig. 15. Cylindrical shell that was welded by the gas metal-arc and consumable-guide-tube electroslag processes, with cross-sectional view of joints (Example 367)

Production Requirements. Both systems are adaptable to repetitive and one-of-a-kind jobs, but the conventional system of electroslag welding is better suited to repetitive work and the consumable-guide-tube system to a variety of short-run work.

Equipment utilization is an important consideration in choosing between the two systems, because the cost of conventional-system equipment cannot be justified for part-time utilization.

Equipment Cost. Equipment required for the conventional system costs from four to five times as much as that needed to do the same job by the consumable-guide-tube system. To a great extent, this difference accounts for the more extensive use of the consumable-guide-tube system. Use of the conventional system is restricted mainly to applications in which the practical limits of the consumable-guide-tube system are exceeded.

APPENDIX

Electroslag Welding of Ship Plate

Neither the conventional system nor the consumable-guide-tube system of electroslag welding as described in the main portion of this article is well adapted to the welding of ship plate in the vertical position, principally because the thickness of ship plate is generally less than is practical for welding by either system of electroslag welding. Except for the well-known manual and semiautomatic arc welding methods, electrogas welding has been the most widely used process for this application.

There is, however, electroslag welding equipment available that is practical for welding plates within the thickness range of ½ to 2 in. and for the long joints normally required in ship construction. Welding with this equipment is fundamentally the same as conventional electroslag welding, as described in this article. However, the details of equipment and operation of the equipment vary considerably.

Equipment designed especially for welding ship plate (but usable also for similar other applications) differs in several respects from equipment used for conventional electroslag welding. The major differences are in the arrangement of equipment components and the method of moving the welding head. Minor differences include many design features that permit a unitized head.

The equipment consists primarily of a mobile unit, often referred to as the crawler assembly because it moves vertically up the plates. In addition, a power supply, electrode-wire supply and water supply, all remotely located, are required.

The crawler assembly consists of two structural frames that ride on the front and back of the workpiece and are connected through the gap, above the welding area, by a ball-lock pivot pin for rapid setup and removal. The front frame carries the drive motor and gear-reducer/transmission unit, a flux dispenser, a tensioning device, a wire-guide assembly, and an articulated welding dam (shoe). The rear frame of the crawler consists of a set of leading rollers, a guide fin, and a second articulated welding dam. The crawler assembly is designed to pass through strongbacks that have a minimum opening 4 in. wide by 2½ in. deep.

Vertical movement is achieved by means of a 60°-V-shape knurled roller that rides on the corner edges of the plates, in the gap, above the welding area. The knurled roller is driven by the motor mounted on the unit. Thus, no overhead suspension or vertical track is required as in most conventional electroslag welding (see the section on Principles of Operation, on page 384 in this article).

The crawler type of welding machine requires a constant-voltage power supply capable of providing 38 volts at 325-amp output and 47 to 48 volts at 550-amp output. Because of the long cables normally needed for this type of application, the voltage drop is usually high. The power supply must incorporate a motorized voltage adjustment.

This welding equipment utilizes a completely enclosed wire-feed system mounted in the control cabinet. The cabinet also houses two electronic governors, a 65-lb-capacity wire reel, and all electrical circuitry for operation and control of the crawler unit. Access to all components is provided through hinged doors located on the cabinet. Four lifting rings are provided to permit suspension of the control unit to follow the plate crawler during welding. This part of the equipment is often suspended on a chainfall so that it can be relatively close to the welding area.

Electrode wire is supplied by a heavy-duty, two-speed wire feeder incorporating an external gearshift that allows selection of either a 29-to-1 or a 95-to-1 gear ratio. The unit, in conjunction with its electronic governor control, feeds electrode wire through an interconnecting conduit to the weld zone at a controlled rate.

For welding in areas where a plant water supply is not available, a specially built water cooler can be used. Such a unit provides cooling water at a rate of 3 gal per minute at 100 psi. The circulating system includes an adjustable pressure-relief valve, a water filter, a visible water-flow indicator, a water-pressure gage and control valve, and an air-pressure-release valve for reverse air flushing. This unit also can be suspended on a chainfall if desired, so as to lessen the distance between the water-cooling unit and the welding unit. A junction box, which is supplied as one component of the equipment, provides a convenient terminal for connecting the water lines to the dams. This box contains bulkhead fittings, and safety switches that automatically shut off the welding current in the event of a water-flow failure.

Operation. The crawler unit is installed in the plate gap and adjusted to the proper tension. Wire feed is preset. An initial starting charge of iron powder and flux is placed in the joint gap, where welding is initiated by an arc as in other electroslag welding operations. As the electrode wire is fed into the joint, a flux depth of ⅝ to 1⅛ in. is maintained. The welding unit (crawler) can be adjusted to move at a rate of ½ to 2½ in. per minute.

Once started, the operation is essentially automatic, although it must be monitored by an operator. Periodic adjustments are required to ensure uniform results.

Electrogas Welding

ELECTROGAS WELDING is an automatic method of gas metal-arc or flux-cored arc butt welding (depending on whether the consumable electrode is a solid wire or a flux-cored tubular wire) in which external shielding gas is supplied and two water-cooled dams (molding shoes) confine the molten weld metal. Although the axis of the weld is vertical, the process is actually flat-position welding with vertical travel, because the consumable electrode is fed downward into a cavity formed by the opposing faces of the components to be welded and the two water-cooled dams (see Fig. 1).

In its mechanical aspects, and its application to welding practice, electrogas welding resembles conventional electroslag welding, from which it was developed (see the article on Electroslag Welding, which begins on page 383). Electrically, electrogas welding differs from electroslag welding in two ways: (*a*) the heat is produced by an electric arc and not by electrical resistance of a slag; and (*b*) only direct current can be used, whereas either alternating or direct current can be used for electroslag welding.

Applicability

Electrogas welding is most often used for joining relatively thick plates, such as those required in the construction of ships, bridges and large tanks (see the section in this article on Welding of Tanks, and Example 368). Large-diameter thick-wall pipes and circular pressure vessels also can be butt welded by the electrogas process, provided that the work can be positioned to permit vertical feeding of the electrode (see the section in this article on Circumferential Welding).

Metals Welded. The electrogas process has been generally restricted to the welding of low-carbon and medium-carbon steels, although it has been successfully used for the welding of alloy steels and the austenitic grades of stainless steel.

Base-Metal Thickness. Electrogas welding is most suitable for the joining of plates within the thickness range of ½ to 3 in., although plates ⅜ in. thick and 4 in. thick have been welded successfully by the process. For the welding of plates thinner than ½ in., shielded metal-arc, gas metal-arc, flux-cored arc, and submerged-arc welding usually are more economical. For plates thicker than 3 in., electroslag welding is usually more practical, because of the difficulty in obtaining adequate shielding-gas coverage (inadequate coverage results in weld defects).

With the use of specially shaped dams it is possible to weld together two plates that differ in thickness by as much as 50%, provided that both plates are within the thickness range of ⅜ to 4 in. prescribed for electrogas welding.

Length of Joint. There is no established limit on the length of joint that can be welded by the electrogas process. In shipyards, joints 80 ft long have been welded in one pass, with the joint in the vertical position. Single-pass welding is the method most frequently employed, but a two-pass method can also be used (see Example 369 and Fig. 8).

Equipment

The essential components of equipment for electrogas welding are a power supply, an electrode holder, water-cooled dams, a system for feeding the electrode wire, a mechanism for oscillating the electrode holder, and devices for supplying shielding gas to the area immediately above the weld puddle. Except for the power supply, the major components of the equipment are incorporated in an assembly that moves as an integral unit as welding proceeds.

A typical unit for electrogas welding is shown in Fig. 1. This unit is suspended on two chains that raise and lower it, as required, by means of a motor-driven hoisting mechanism (not shown in Fig. 1). (Other units are suspended by a single chain or by cables, or a track may be employed.) In addition to the components shown in Fig. 1, the unit incorporates control devices

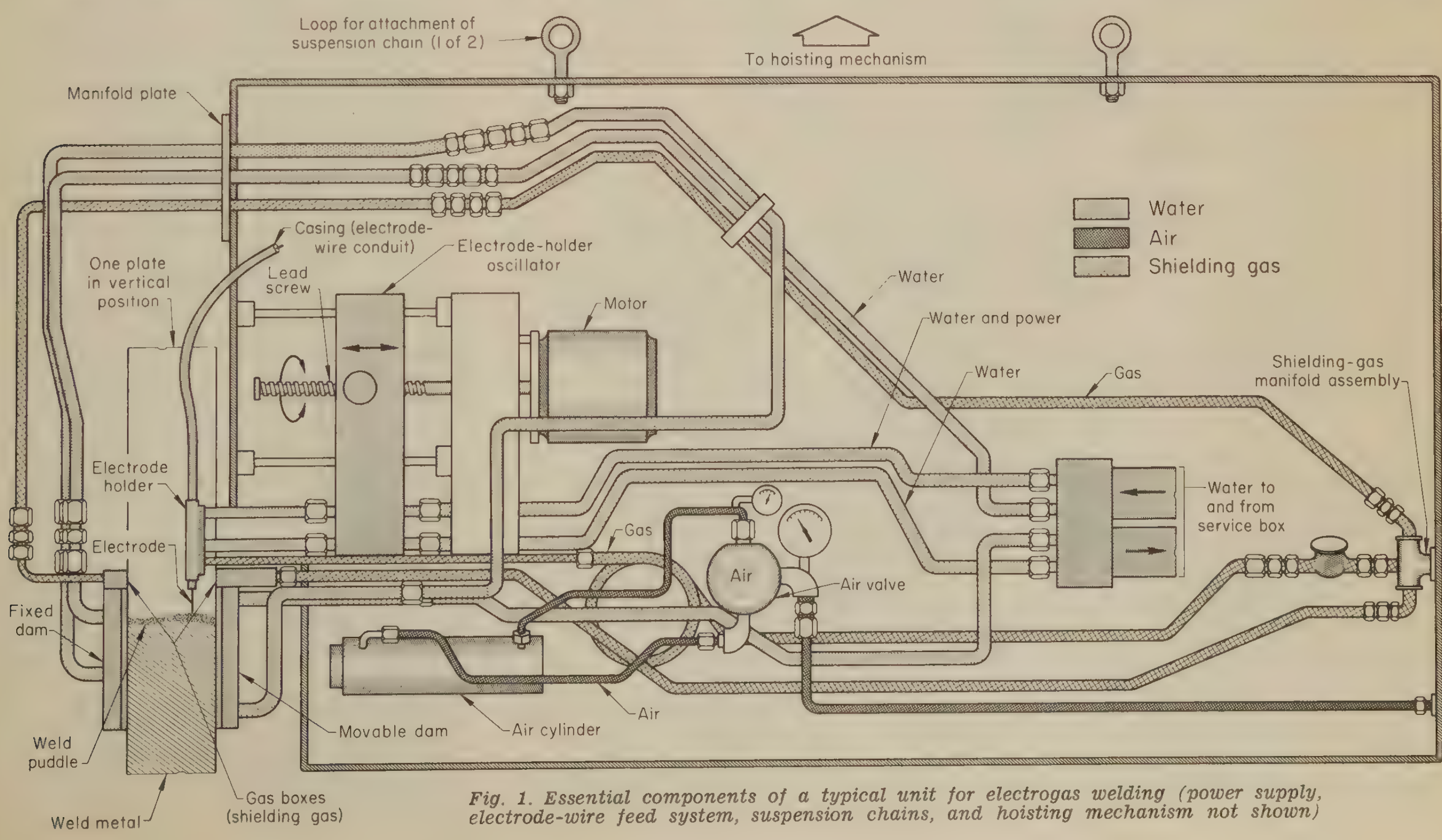


Fig. 1. Essential components of a typical unit for electrogas welding (power supply, electrode-wire feed system, suspension chains, and hoisting mechanism not shown)

for maintaining the required welding voltage and current, electrode-wire feed rate, shielding-gas flow rate, welding speed, and cooling-water flow rate.

The arrangement of the joint assembly (plates in a vertical position), water-cooled dams, gas boxes, and the electrode holder for one system of electrogas welding is shown in Fig. 2(a). Details of the electrode holder, a gas box, and the fixed dam (so called because it cannot move in the horizontal plane) are shown in Fig. 2(b), (c) and (d). The workpieces are held in position during welding by conventional strongbacks. Shielding gas is supplied through ports of two separate gas boxes (Fig. 2c), one on each side of the joint being welded. In this system, the electrode holder (also called the contact-tube guide or the wire guide) has a duct through which a part of the shielding gas is supplied.

Figure 3 shows the arrangement and details of essential components for another system of electrogas welding. In this system, shielding gas is supplied through ports incorporated in the water-cooled dams (see Fig. 3c); therefore, no separate gas boxes are needed.

Power Supplies. Electrogas welding is done with reverse-polarity direct current, normally supplied by a transformer-rectifier. Motor-driven and engine-driven generators are also used, but to a lesser extent. The power supply may be of either the constant-current or constant-voltage type; the constant-current type is used for a welding unit in which vertical travel is controlled by changes in arc voltage (see the discussion under "Control of Vertical Travel", on page 399).

Because current demands are usually heavy and duty cycles are often long, the power-supply unit must be rugged. Power supplies having capacities that exceed the maximum anticipated current demand are recommended. Most power supplies used have capacities of 750 amp or more at 100% duty cycle.

(For a more detailed discussion of power supplies used in welding, see page 3 in the article on Shielded Metal-Arc Welding and page 80 in the article on Gas Metal-Arc Welding.)

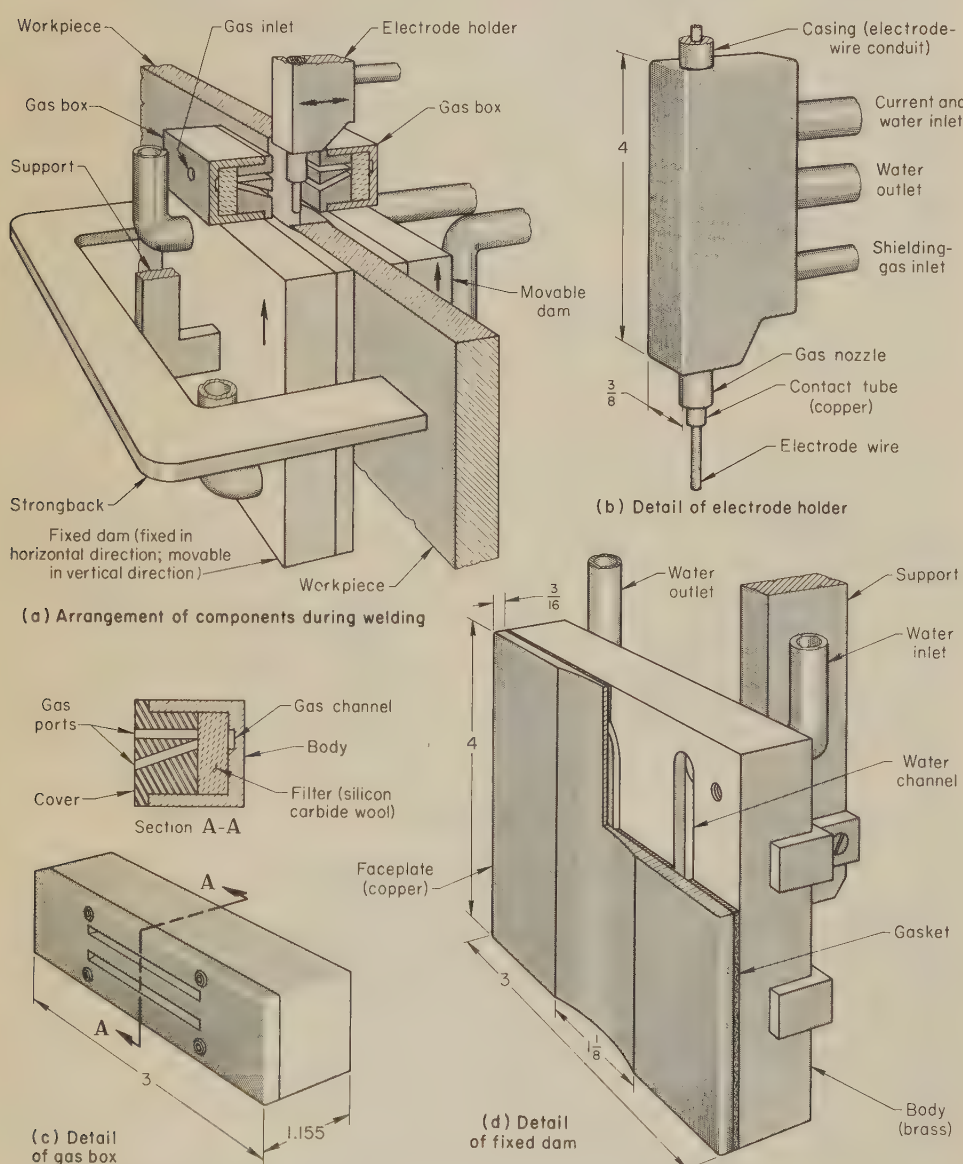


Fig. 2. Arrangement and details of essential components of an electrogas welding system employing a water-cooled electrode holder and separate gas boxes

Electrode holders for electrogas welding serve essentially the same purpose as those used in automatic gas metal-arc and flux-cored arc welding. However, they differ considerably in design for different electrogas systems (compare Fig. 2b and 3b). Regardless of the system used, the electrode holder must be narrow enough to clear the two plates being welded as it moves vertically within the gap between them. For this reason, the width of an electrode holder usually is limited to about 3/8 in.

A typical water-cooled electrode holder is shown in Fig. 2(b). The body of this holder contains cooling-water ducts and a duct for carrying shielding gas. The power supply is connected to the contact tube, which is made of copper and transmits the current to the electrode wire as it passes through, as in gas metal-arc welding. Water-cooled electrode holders are more complex, and therefore cost more, than holders that are not water cooled; water cooling, though, provides longer service life.

A typical non-water-cooled electrode holder is shown in Fig. 3(b). This holder serves only to guide the electrode wire and to carry the current; it has no duct for carrying shielding gas. It consists essentially of a curved contact tube of heat treated beryllium copper, held between and brazed to a pair of copper supports, and a copper bracket for mounting the assembly to the welding unit. The electrode holder is wrapped with insulating tape to protect it from the heat and from accidental arcing if it touches the sidewalls of the joint. Even so, the end nearest the weld puddle becomes extremely hot and gradually deteriorates. The deteriorated end can be cut off, and the electrode holder can be used for an application where a shorter electrode holder is acceptable.

Water-Cooled Dams. In most electrogas welding, two water-cooled dams (also called molding shoes) are used to form the cavity for the molten weld metal, to retain the weld metal until it solidifies (in most applications, the dams form two sides of the cavity), and to provide shape to the weld reinforcement. The dams move vertically with the welding unit. Water cooling prevents the molten metal from welding to the dam, and hastens solidification.

In one system, one dam is called the fixed dam, and the other, the movable dam (Fig. 2a). (The terms fixed and movable refer only to horizontal movement; both dams move vertically.) The fixed dam is held by a rigid support to prevent it from moving horizontally. The movable dam is actuated by an air cylinder and is moved horizontally to accommodate plates of different thicknesses. The pressure from the air cylinder also ensures that the dams are always held securely against the work.

In the system shown in Fig. 3(a), the two dams are pressed against the work by vise action through a cantilever arm that is spring loaded to relieve excessive pressure when the dams ride over minor obstructions.

The design of the dams varies considerably, depending on whether or not shielding-gas ducts are incorporated in them. A fixed dam without ducts for shielding gas is shown in Fig. 2(d). (The movable dam is essentially the same

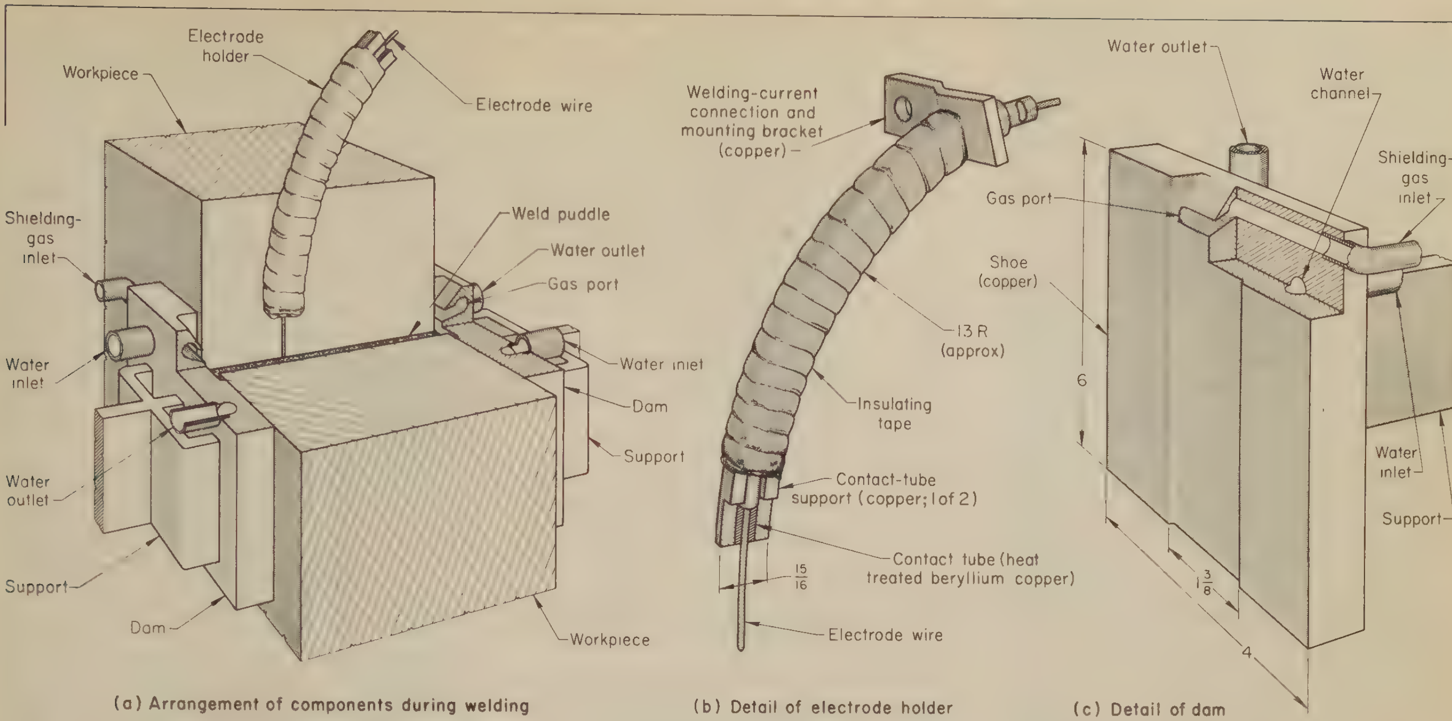


Fig. 3. Arrangement and details of essential components of an electrogas welding system employing an insulated electrode holder and dams that incorporate ports for supplying all shielding gas

except for the method of mounting.) This dam has a brass body that contains channels for circulation of cooling water. A copper faceplate is secured to the brass body, with an intervening gasket to act as a water seal. Faceplates are made of copper because of its high thermal conductivity; they are subject to damage in handling. The two-piece construction of the dam permits replacement of the faceplate without replacing the entire dam, and also makes it simpler to machine the water channels in the brass body.

The concave section in the middle of the faceplate on the dam shown in Fig. 2(d) straddles the joint as the dam moves vertically during welding. The width of this concave section is fairly critical; for example, the 1⅛-in. width shown in Fig. 2(d) is intended for welding plates separated by an 11⁄16-in. gap, using a solid electrode wire. It is not customary to leave a gap between the dam and the work, but should such a gap exist, the extra width of concave section that extends beyond each side of the joint allows any molten metal that starts to flow between the work and the dam to solidify before reaching the outer edges of the concave section. If flux-cored electrode wire is used, the width of the concave section should be increased to about 1¼ in., and the depth of the concave section should be increased correspondingly, to allow room for slag accumulation with the required weld reinforcement.

A dam that incorporates channels for both cooling water and shielding gas is shown in Fig. 3(c). The use of this dam (covered by U. S. Patent 3,281,570) eliminates the need to supply additional shielding gas through the electrode holder. The dam is of one-piece construction in solid copper and its gas port is designed to provide uniform shielding of the weld area without turbulence. The recessed area on the face of the dam differs slightly in dimensions and shape from the concave section shown in Fig. 2(d), but it serves the same purpose.

Electrode-wire feed systems are of the push type, and are similar to those used for gas metal-arc welding. (See the section on Wire-Feed Systems on page 82 in the article on Gas Metal-Arc Welding.) In addition to the reel of electrode wire, the feed rolls, and the casing (wire conduit) through which the electrode wire is pushed, the system may include a wire straightener, located between the reel and the feed rolls.

Electrode-Holder Oscillators. Most units for electrogas welding incorporate an oscillator mechanism for the electrode holder. Oscillation is generally required when welding sections thicker than 1 in., but it is sometimes used for thinner sections. There are several types of mechanism for achieving oscillation of the electrode holder. One common type, shown schematically in Fig. 1, consists of a motor-driven lead screw that moves an oscillator plate connected to the electrode holder.

Gas Ports. Shielding gas must be supplied, uniformly and without turbulence, above the weld puddle. In one system, part of the shielding gas is supplied through two separate components, called gas boxes, and supplementary shielding gas is supplied through the electrode holder. One gas box is mounted on the top of each dam, as shown in Fig. 2(a). Each gas box is constructed with a gas inlet (Fig. 2a), a gas channel, and slot-shape gas ports (Fig. 2c). Common practice is to drill the inlet hole to a diameter that will permit an adequate supply of shielding gas to be fed into the box under some preselected line pressure.

In another system, all of the shielding gas is supplied through ports in the dams (see Fig. 3c), and no supplementary shielding is required.

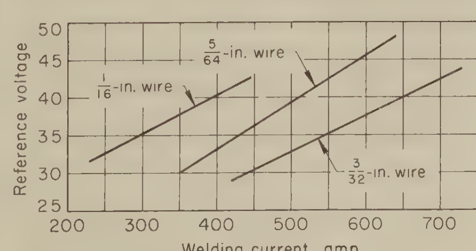


Fig. 4. Relations between reference voltage and welding current for three sizes of solid electrode wire in electrogas welding

Electrode Wires

Either solid or flux-cored electrode wire (filler metal) can be used in electrogas welding. Regardless of the type, preferred practice of one equipment manufacturer is to process the wire through a straightener before it enters the feed rolls.

Solid electrode wires are the same as those used for gas metal-arc welding (see Table 1 in the article on Gas Metal-Arc Welding for AWS classifications and compositions). Sizes most commonly used are 1⁄16, 5⁄64 and 3⁄32-in. diameter. Typical relations between reference voltage and welding current for these three sizes of electrode wire are shown in Fig. 4.

Flux-cored electrode wires used for electrogas welding are often of special composition and do not necessarily conform to AWS specifications (see Table 1 in the article on Flux-Cored Arc Welding). The tubular portion of the electrode is made of low-carbon steel, and the core is composed of flux and alloying elements as needed to meet the mechanical-property requirements of the welded joint. The most commonly

used sizes of flux-cored electrode wire are 1/16, 5/64 and 3/32-in. diameter.

Flux-cored electrode wires for electrogas welding normally have a lower flux-to-metal ratio than those for flux-cored arc welding. One flux-cored wire used in electrogas welding contains only about 6% flux by volume. Some electrode wires designed for flux-cored arc welding are likely to provide an excess of flux and result in choking of the arc when used for electrogas welding of long joints. With low-flux electrodes, joints 48 ft long have been electrogas welded in one pass with no arc choking.

For welding of low-carbon steel, the unit cost of flux-cored electrode wire is more than that of solid electrode wire. In one application, for example, 1/16-in. flux-cored wire cost $0.575 per pound and 1/16-in. solid wire cost $0.345 per pound, quantity and other conditions being the same. For alloy steel electrodes, solid wire often costs more than flux-cored wire, because alloy steel wire is subject to alloy extras, whereas alloying elements are added in powder form to the core of a flux-cored wire.

In welding of low-carbon steel, the higher cost of flux-cored wire is often justified because flux-cored electrode wire has about 20% greater deposition rate than solid electrode wire. Deposition rates typical of two sizes of solid and flux-cored electrode wire are:

Diam, in.	Solid	Flux-cored
1/16	18 lb per hr	22 lb per hr
5/64	24	29

Stickout. In most electrogas welding, electrode stickout of about 1½ in. is used. This relatively long stickout increases electrode melting efficiency by providing preheating of the wire.

Shielding Gases

A mixture of approximately 80% argon and 20% carbon dioxide is widely used, and is generally preferred, as a shielding gas for most electrogas welding applications. This mixture is well suited for use with both solid and flux-cored electrode wire.

Carbon dioxide alone is also used and is particularly satisfactory when employed with flux-cored wire.

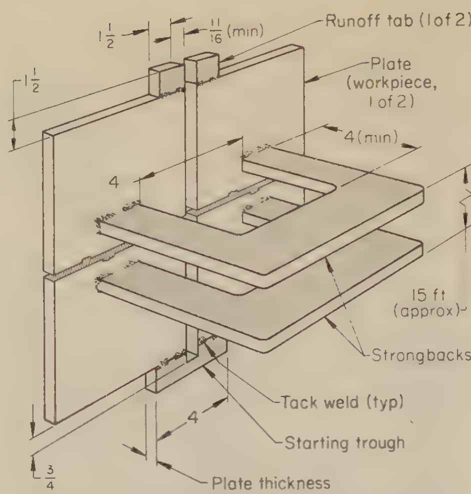


Fig. 5. Two plates with starting trough, runoff tabs, and strongbacks, in position for electrogas welding

Workpiece Assembly

Figure 5 shows two steel plates that have been assembled in a typical joint for electrogas welding. Both a starting trough and runoff tabs are used, to permit deposition of weld metal beyond the ends of the joint. The need for starting troughs and runoff tabs depends mainly on plate thickness and on the extent to which repair welding (usually by the shielded metal-arc process) can be tolerated. Plates less than about 1 in. thick can usually be welded satisfactorily without the use of runoff tabs and by using only a starting block instead of a starting trough. Plates thicker than 1 in. can be welded in the same way, but as plate thickness increases, the amount of repair welding required will be greater if a starting trough and runoff tabs are not used.

As Fig. 5 shows, the starting trough and runoff tabs have the same thickness and width of gap as the plates to be welded, and are tack welded in place. The depth of the starting trough and the height of the weld metal deposited in the runoff tabs vary, depending on the specific equipment and the application requirements. Ordinarily, a ½-in. starting-trough depth and runoff-tab height are sufficient, but these may be increased to as much as 1½ in. for thicker sections. In one plant, 2 in. is the standard depth of starting troughs and height of runoff tabs.

When many identical joints are to be welded, the starting trough and the runoff tabs are often made of copper and are usually air cooled. Instead of being tack welded, they are clamped in place, thereby shortening setup time, and can be reused many times.

Usually, the plates to be welded are temporarily held in position by as many strongbacks as are needed to obtain rigidity. The cut-out portion of strongbacks must accommodate the fixed dam and usually must not be smaller than 4 by 4 in., as shown in Fig. 5, so that the dam can pass through as it travels up the joint.

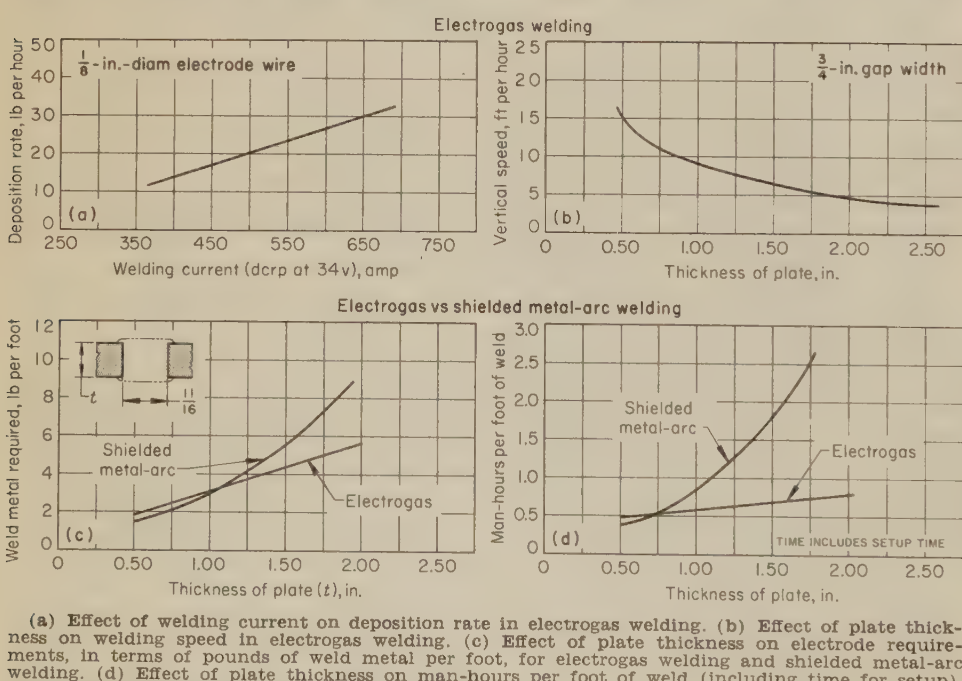
The gap between the plates does not vary with plate thickness. A minimum gap of 11/16 in. (Fig. 5) is commonly used.

Operating Procedure

In setting up for electrogas welding, the entire welding unit is installed over or beside the joint between the two plates. Travel is checked by lowering and raising the unit, making certain that the electrode holder enters and leaves the gap smoothly and remains centered in the gap. During setup, other adjustments, including feed rate of the electrode wire, reference voltage, and current, are made. Electrode-wire size and required deposition rate must be considered in making the initial settings. If experience with similar applications is not available, the best procedure is to use the data supplied with the particular machine as a starting guide. However, sample welds should be made and tested to ensure that the welding procedure will provide joints having the required properties.

After the preliminary adjustments have been made, a button is pushed to start the automatic welding operation. First, the weld area is purged with gas, then the electrode wire is fed, the arc is struck, and welding begins. After the arc is established and becomes steady, correction of the current control may be required. Current variations of about ±25 amp caused by fluctuations in line voltage can be tolerated for short periods of time, but if the welding current stays off the pre-established value for more than about half a minute, it should be adjusted to bring it to the pre-established value.

Oscillation. Thickness of the work metal determines whether or not the electrode holder will be oscillated during welding. When the work metal is



(a) Effect of welding current on deposition rate in electrogas welding. (b) Effect of plate thickness on welding speed in electrogas welding. (c) Effect of plate thickness on electrode requirements, in terms of pounds of weld metal per foot, for electrogas welding and shielded metal-arc welding. (d) Effect of plate thickness on man-hours per foot of weld (including time for setup), for electrogas welding and shielded metal-arc welding.

Fig. 6. Relation of welding variables and welding-process efficiency (Example 368)

less than 1 in. thick, oscillation usually is not required, although it may be used in certain applications. If oscillation is used, it is necessary to make the adjustments during setup.

The oscillator mechanism moves the electrode holder back and forth within the gap. This is commonly accomplished with a lead screw, as shown in Fig. 1. The length of travel can be varied, but is usually set so that the electrode holder stops at a distance of ⅜ in. from each dam. The speed of traverse during oscillation is commonly 16 to 18 in. per minute. The oscillation cycle is normally set to incorporate a dwell time of up to 3 sec at each side before the direction is reversed. Dwell time near each water-cooled dam is used to achieve satisfactory penetration into the workpiece sidewall near the outer face that abuts the dam. If the dwell time is insufficient, the cooling effect of the copper dam causes lack of fusion of the base-metal surface.

Control of Vertical Travel. Close control of vertical travel is necessary, to maintain constant arc length and uniform arc voltage.

The method used for control of vertical travel depends mainly on the type of power supply used. A constant-current (drooping voltage) power supply enables travel to be controlled by a change in arc voltage. If, for example, the reference voltage (set on the machine) is 35 volts, there will be no movement until the arc voltage drops below 35. When this occurs, the travel mechanism is automatically actuated and the unit moves upward until the arc voltage is restored to its former value. The equipment is sensitive to a reduction as small as ¼ volt.

When a constant-voltage power supply is used, another means of controlling vertical travel must be sought. One system employs a photoelectric cell that controls the rate of travel by observing the height of the rising weld puddle.

To obtain the required control of travel speed, some minor adjustments by the operator are commonly required at the beginning of welding and, occasionally, from time to time during an extended welding cycle.

Welding of Tanks*

The electrogas process has been used successfully for making the vertical welds on field tanks built to various code specifications. A major reason is that thickness of plates used in construction of these tanks is usually within the range where the electrogas process can be applied most efficiently.

Because such tanks are large, duty cycles are long and the amount of welding done at one site is large. These conditions favor rapid amortization of electrogas equipment, which is considerably more costly than equipment for shielded metal-arc or other arc welding processes.

In one plant a development program was carried out to evaluate the relationships of some of the common welding variables and to compare efficiencies of electrogas welding and of shielded metal-arc welding for use in joining plates of the thickness range most widely used for tank construction (approximately ½ to 2 in.). Results of this investigation are given in the example that follows.

*This section, including Example 368 and Fig. 6, is based on information presented in the article Automatic Vertical Welding and Its Industrial Applications, by R. J. Franz and W. H. Wooding, *Welding Journal*, June 1963.

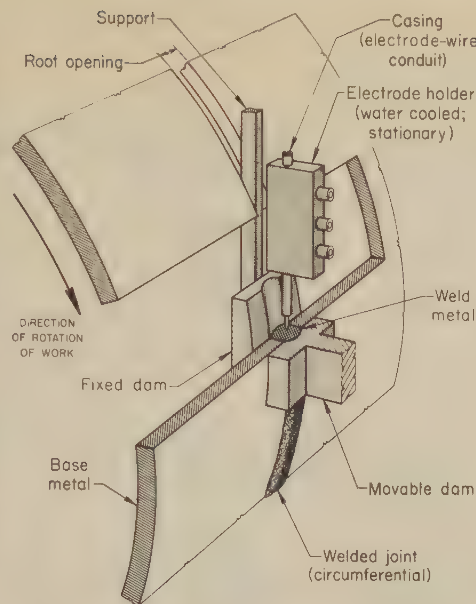


Fig. 7. Typical setup for circumferential (girth) welding by the electrogas process

Example 368. Development Program To Determine the Interrelation of Welding Variables and Efficiency of the Electrogas Process for Welding of Tanks (Fig. 6)

With the exception of Fig. 6(a), wherein amperage is one of the variables, a welding current of 650 amp dcrp at 34 volts was used to develop the data on electrogas welding shown in Fig. 6. As seen in Fig. 6(a), deposition rate has a straight-line relation to current in electrogas welding. With a current of 650 amp and a ⅛-in.-diam low-carbon steel electrode wire, a deposition rate of 30 lb per hour was obtained as shown in Fig. 6(a). The deposition efficiency was approximately 95%. Figure 6(b) shows the speed of electrogas welding, in feet per hour for 100% arc time, as a function of plate thickness, using a ¾-in. gap.

Figure 6(c) shows the electrode requirements in pounds of weld metal per foot for electrogas welding versus shielded metal-arc welding as a function of plate thickness, using an ¹¹⁄₁₆-in. gap. It should be noted that the electrode requirements plotted for electrogas welding form a straight line, whereas the shielded metal-arc requirements are on a curve of continually increasing slope. This is because of the square-cut joint edges used for the electrogas process, in contrast to the V-groove joint used for shielded metal-arc welding. Figure 6(d) compares the total time requirements for electrogas welding and shielded metal-arc welding. From these curves it can be seen that electrogas welding can be used for welding plates as thin as ½ in., but that it is less efficient than the shielded metal-arc process as plate thickness decreases to slightly below ¾ in. This is due in part to the initial setup time required, but mostly because a two-man crew was required to operate the electrogas machine.

The electrogas process thus proved to be economical, not only because of its ability to make acceptable welds at high deposition rates, but also because base-metal preparation was simple. For electrogas welding, edge preparation was simply a square-cut surface obtained by shearing or gas cutting. It was necessary only that the surfaces to be welded form a rectangular opening. Although fit-up and surface alignment should be held to reasonable tolerances, it was found that such tolerances may be exceeded to a considerable extent without any adverse effect on weld quality or finished appearance of the joint. The minimum gap between the surfaces to be welded was held to ¹¹⁄₁₆ in., because this minimum opening was needed to accept the electrode holder without difficulty of arcing on the surfaces of the joint. However, it was found that the gap could vary from ¹¹⁄₁₆ to ⅞ in. in any joint without causing difficulty other than that of adjusting the vertical travel speed to accommodate the differences in quantity of weld metal required.

Typical Applications. Four applications involving the use of electrogas welding for vertical joints in large outdoor tanks are briefly described below.

Surge Tanks. Fourteen tanks 70 ft in diameter and 145 ft high were constructed for use as surge tanks and were located between the penstocks and the powerhouse near a large dam. These tanks were fabricated from ASTM A515 or A516 carbon steel plates ranging in thickness from 1¾ in. for the bottom course to ⅜ in. for the top course. The tanks were built in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code, and in accordance with the Corps of Engineers specifications. Welded seams were subjected to x-ray examination.

Cement slurry tanks 150 ft in diameter by 37 ft high were constructed from ASTM 515 or 516 steel to conform with API-12C specifications. Plate thickness in these tanks ranged from 1³⁄₁₆ in. for the bottom course to ⅜ in. for the top course.

Storage Tanks. A group of three storage tanks was built from ASTM A285 steel in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code. The two bottom courses were 1½ in. thick and the remaining 13 courses were made of plates 1³⁄₁₆ in. thick.

Water Reservoirs. Three tanks for water reservoirs were constructed in accordance with AWWA D-100 and AWS D5.2 specifications. Each of these tanks was 338 ft in diameter and 16 ft high and was constructed with two courses. Plates for the lower course were 1⅛ in. thick, and for the upper course were ⁹⁄₁₆ in. thick.

Circumferential Welding

Circumferential (girth) welding of large-diameter pipes or pressure vessels can be done efficiently by the electrogas process. The method used differs from welding straight vertical sections of similar thickness in two respects: (*a*) the dams must be made to fit the curvature of the joint to be welded, and (*b*) the welding equipment remains stationary and the workpiece is rotated.

Circumferential welding can be done by more than one procedure. In one common method, shown in Fig. 7, the equipment components, with the exception of the curved dams, are the same as those used for vertical welding of plates. Welding proceeds as the workpiece rotates in a clockwise direction. The water-cooled electrode holder remains stationary, although it could be oscillated if required. The fixed dam is curved to fit the inside contour of the workpiece, and does not move in either the vertical or horizontal plane. The movable dam is curved to fit the outside contour of the workpiece and can be moved horizontally only, to accommodate variations in wall thickness.

A disadvantage of using the method shown in Fig. 7 is that when all but

approximately 18 in. of the circle has been welded, the electrogas equipment must be removed and the weld must be completed by another welding process, such as shielded metal-arc, gas metal-arc, or flux-cored arc welding. The seriousness of this disadvantage depends mainly on the wall thickness and the circumference of the sections to be joined. If the wall thickness were less than 1 in. and the circumference 30 ft, the amount of welding to be completed (in proportion to the total amount of welding) would be relatively small. On the other hand, if the wall thickness were 2 in. and the circumference only 10 ft, the amount of welding required for completion might be considered great enough to warrant the use of another process for the entire weld, or at least an alternative method of electrogas welding.

Alternative methods of circumferential welding, developed primarily for electroslag welding, and described in the article that begins on page 383, have also been applied successfully to electrogas welding. In one of these methods, circumferential welding begins on a starting block inserted between the two sections to be welded. The fixed dam is fastened on the inside of the joint area. Preparation for the closing sequence is made when the weld is half completed, by cutting away the starting block and gouging out the initial weld along a predetermined surface and tangential to it until the inner surface is reached. Tapered finishing tabs are tacked in place outside the joint at this location, so that the weld crater can finally be brought to the surface of the cylinder as the joint is finished. The weld is completed with the cylinder stationary and the electrode holder rising, as in a vertical weld.

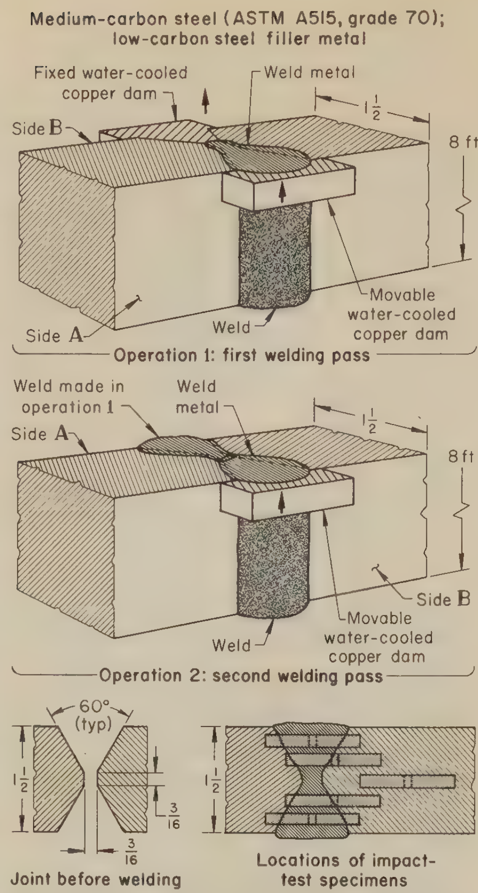
Two-Pass Welding

Most electrogas welding is done in a single pass, using square-groove butt joints, as shown in Fig. 5, but a type of joint that requires two-pass welding, such as a double-V-groove joint, may be needed (see Example 369 and Fig. 8). For two-pass welding, specially shaped dams are required. For instance, in welding a double-V-groove joint, the fixed dam must be contoured to fit the V for the first pass (see Fig. 8). After the workpiece is turned 180° (or the welding unit is moved), the second pass is made with only the movable dam; the first-pass weld performs the function of a fixed dam. Back gouging or grinding of the root of the first pass is required before the second pass can be deposited.

Two-pass welding has two metallurgical advantages over single-pass welding: (*a*) the shallower weld deposit requires lower heat input, and thus grain growth is minimized; and (*b*) the second pass generates enough heat to provide a grain-refining heat treatment for the weld made on the first side.

Electrogas vs Electroslag Welding

The equipment for electrogas welding closely resembles that for conventional electroslag welding. Therefore, a change from one process to the other entails



Location of impact-test specimen (see view at bottom right, above)	Testing temperature, F	Energy absorbed, ft-lb
Charpy V-Notch Impact Strength		
Plate as received	70	17
	50	7
Weld metal, side A	70	80
	30	60
Weld metal, side B	70	65
	30	45
Heat-affected zone:		
Side A	70	24
Side B	70	18
One-pass electroslag weld	70	10

Conditions for Electrogas Welding

Joint type .... Butt
Weld type .... Double-V-groove
Electrode wire .... ⁷⁄₆₄-in.-diam, flux-cored
Current (both passes) .... 475 amp, dcrp
Voltage ....34 v, first pass; 36 v, second pass
Arc length .... ¼ in., approx
Shielding gas .... Carbon dioxide, at 30 cfh
Welding position ...... Flat (vertical-axis weld)
Welding speed, both passes .... 3 ipm
Preheat .... None
Postheat .. Stress relief (if required for service)

Fig. 8. Section of an 8-ft-high vessel erected in the field, showing details of a two-pass electrogas weld that had greater notch toughness than a one-pass electroslag weld (Example 369)

simply a change from shielding gas to flux, or from flux to shielding gas. Thus, selection between processes is based on cost and application requirements, not on capital expenditure.

For work metals ¾ to 3 in. thick, the electrogas and conventional electroslag processes are often closely competitive. Some advantages of the electrogas process over electroslag welding are:

1 Restarting the weld is much easier.
2 The weld is much more visible to the operator.
3 As-welded impact properties are better. Thus, electrogas welding often is chosen if no heat treatment follows welding.

Offsetting these advantages is the fact that the electroslag process usually produces welds that are cleaner and more nearly crack-free. Also, when electrogas welding and shielding gas are used, porosity generally increases as base-metal thickness increases, because shielding becomes less effective.

The choice between the two processes for work metal ¾ to 3 in. thick is sometimes influenced by the properties obtainable in the completed weld. This was the case in Example 369, where electrogas welding produced tougher welds.

For sections more than 3 in. thick, electroslag welding is usually more practical. When applicable, the electroslag process that uses a consumable guide tube may cost less than electrogas welding, because the capital investment for the consumable-guide-tube electroslag process is only about 20% of that for the electrogas process. For welding low-carbon steels such as ASTM A36 in applications for which impact requirements are not stringent, the electroslag process is more often chosen because of its higher deposition rate.

Weld Properties. In welding large steel vessels, it is rarely possible to provide postweld heat treatment to improve the mechanical properties of the weld metal and of the heat-affected zone, and so the welding process used must be one that will ensure adequate toughness in the as-welded condition. In some applications, the low heat input and fast cooling of the weld metal in electrogas welding have made it possible to obtain specified mechanical properties that could not be obtained by electroslag welding. One such application is described in the next example.

Example 369. Two-Pass Electrogas Welding That Produced Tougher Welds Than One-Pass Electroslag Welding (Fig. 8)

A vertical weld 8 ft high was made by the electrogas process in the field erection of a vessel fabricated from 1½-in.-thick ASTM A515, grade 70, steel plate. Welding was done in two passes, one on each side of the plate, as shown in Fig. 8. A water-cooled copper dam with a shaped nose was used as a fixed dam for the first pass; the weld metal of the first pass served as the fixed dam for the second pass. For start-up, a starting trough was used at the bottom of the joint (not shown in Fig. 8). Joint preparation consisted of beveling the plates as shown in the view at bottom left in Fig. 8. Welding conditions are given with Fig. 8.

Impact tests were made using full-size Charpy V-notch specimens cut from the weld metal and heat-affected zone for each weld pass, and on a specimen taken from the as-received plate for comparison; the approximate locations of the specimens are shown in Fig. 8, bottom right. A further comparison was made by impact testing the heat-affected zone of a one-pass weld made by the electroslag process. As shown in the table with Fig. 8, the notch toughness of all specimens from the electrogas welded joint exceeded that of the as-received plate, whereas the notch toughness of the specimen from the heat-affected zone of the electroslag weld was considerably less.

Four side-bend tests and two tension tests of specimens from the electrogas welded vessel were conducted in accordance with Section IX (Welding Qualifications) of the ASME Boiler and Pressure Vessel Code. Code requirements were met in all tests. In the first tension test, tensile strength was 82,500 psi, and elongation in 2 in. was 24%; in the second test, tensile strength was 81,900 psi, and elongation 30%.

RESISTANCE WELDING

CONTENTS

Resistance Spot Welding

*By the ASM Committee on Resistance Welding of Steel**

RESISTANCE SPOT WELDING is a process in which faying surfaces are joined in one or more spots by the heat generated by resistance to the flow of electric current through workpieces that are held together under force by electrodes. The contacting surfaces in the region of current concentration are heated by a short-time pulse of low-voltage, high-amperage current to form a fused nugget of weld metal. When the flow of current ceases, the electrode force is maintained while the weld metal rapidly cools and solidifies. The electrodes are retracted after each weld, which usually is completed in a fraction of a second.

The size and shape of the individually formed welds are limited primarily by the size and contour of the electrode faces. The weld nugget forms at the faying surfaces, as shown in Fig. 1, but does not extend completely to the outer surfaces. In section, the nugget in a properly formed spot weld is obround or oval in shape; in plan view, it has the same shape as the electrode face (which usually is round), and approximately the same size. The spots should be at a sufficient distance from the edge of the workpiece ("edge distance") so that there is enough base metal to withstand the electrode force and to ensure that the local distortion during welding does not allow expulsion of metal from the weld. Also, spacing between adjacent spot welds or rows of spot welds must be enough to prevent shunting or to limit it to an acceptable amount.

Applications. Spot welded lap joints are widely used in joining sheet steel up to about ⅛ in. thick, and are used occasionally in joining steel ¼ in. or more in thickness. Thicknesses of 1 in. or more have been joined by spot welding, but this requires special equipment and would not ordinarily be economical. Many assemblies of two or more sheet-metal stampings that do not require gas-tight or liquid-tight joints can be more economically joined by high-speed resistance spot welding than by mechanical methods. Containers such as receptacles and tote boxes frequently are spot welded. The attachment of braces, brackets, pads or clips to formed sheet-metal parts such as cases, covers, bases or trays is another common application of spot welding.

Major advantages of resistance spot welding are high speed and suitability for automation and inclusion in high-production assembly lines with other fabricating operations. With automatic control of current, timing and electrode force, sound spot welds can be produced consistently at high production rates and low unit labor costs by unskilled operators.

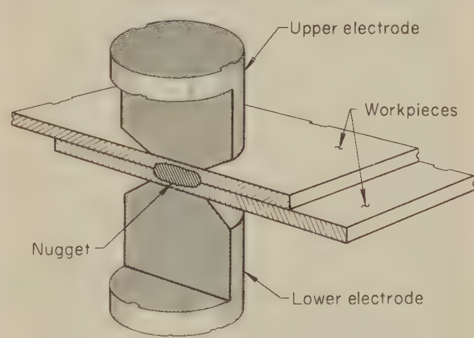


Fig. 1. Arrangement of electrodes and workpieces in resistance spot welding, sectioned to show shape of nugget and position of nugget relative to inner and outer surfaces of workpieces

However, a resistance spot weld in steels, which typically draws a current of about 5000 to 20,000 amperes at about 5 to 20 volts, imposes a heavy kilovolt-ampere (kva) demand. (The kva demand is even higher for resistance spot welding more conductive metals, such as many aluminum alloys and copper alloys.) Even though the duration of current flow for a single weld is only a few cycles, the corresponding power demand may be an undesirable load, especially if power is drawn from only one phase of a three-phase supply. Also, the initial cost of equipment is generally much higher for resistance welding than for most arc welding processes.

Although the most common application of resistance spot welding is the joining of two sheets of metal having the same composition and thickness, the process is also used to join more than two sheets of metal, to join metals that are dissimilar in thickness or composition (or both), and to join steel coated with another metal. The 13 examples of practice presented in this article illustrate the range of application of resistance spot welding to low-carbon steel.

For information on the spot welding of metals other than low-carbon steel, see the articles in this volume on resistance welding of stainless steel (page 456), aluminum alloys (page 466), and copper and copper alloys (page 475).

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Most of the examples in this article were contributed by members of other Metals Handbook welding committees. Additional examples on resistance spot welding that appear in other articles in this volume are listed in Table 8, page 424.

Equipment. Nearly all resistance spot welding of low-carbon steel is direct-energy welding, in which single-phase or three-phase 60-cycle* alternating current, drawn ordinarily from 220-volt or 440-volt in-plant power lines and stepped down to about 2 to 20 volts, is fed directly to the electrodes as each weld is made.

The equipment needed for resistance spot welding may be simple and inexpensive, or complex and costly, depending on the degree of automation. Machines for direct-energy welding generally are composed of the following three principal elements:

1. **Electrical Circuit.** This consists of a welding transformer, a tap switch and a secondary circuit. The secondary circuit includes the electrodes that conduct the welding current to the workpieces.
2. **Control Equipment.** This initiates and times the duration of current flow, and may also be used instead of (or in addition to) the transformer tap switch to regulate the welding current. Controls may also sequence, time and regulate the over-all operation of the machine, including initiation, automatic adjustment, and termination of welding force and current.
3. **Mechanical System.** This consists of the frame, fixtures and other devices that hold and clamp the workpieces and apply the welding force.

Specifications for resistance welding equipment have been standardized by the Resistance Welder Manufacturers' Association (RWMA); and, for controls, by the National Electrical Manufacturers' Association (NEMA).

Single-Phase and Three-Phase Direct-Energy Welding Machines

The choice between single-phase and three-phase direct-energy machines for resistance spot welding is based mainly on machine capability and on initial, operating and maintenance costs. Power factor and load balance among the three phases of the power supply should also be considered, particularly when a high-capacity machine is needed in a plant where the supply of electric power is limited.

Single-phase machines are more widely used than three-phase machines. Single-phase machines are simpler than three-phase machines, and they cost less to buy, install and maintain. When equipped with suitable controls, however, a single-phase machine has the same performance capabilities as a three-phase machine of the same size and rating.

The two disadvantages of single-phase machines are low power factor (about 40 to 50%) and high kva demand (about double that for three-phase machines of the same capacity). Since the demand time for a resistance weld is very short, the amount of electric power consumed in welding may be insignificant. Nevertheless, if the welding-machine load is an appreciable part of the total electrical load in a plant, fixed charges for standby service, connected load, and power factor may be quite high when single-phase machines are used, even though they draw power from only one phase of the three-phase supply. If the welding-machine load is a small part of the total plant electrical load, or is used in industrial areas where ample electric power is available, these fixed charges usually are minor.

The low power factor and high kva demand of single-phase machines are outweighed in most situations by their cost advantages. In plants where many single-phase machines are in use, they can be connected so that the welding-current load is distributed among the three phases of the power supply to reduce the kva demand.

Three-phase machines, which take electric power from all three phases of the power-supply line, are of two general types — frequency-converter and rectifier. They differ from single-phase machines only in electrical construction. The transformer of a single-phase machine has only one primary winding. The frequency-converter three-phase machine has a transformer with three primary windings. The rectifier type has a three-phase-to-three-phase transformer, the secondary circuit of which supplies current to low-voltage rectifiers, which in turn deliver high-amperage, low-voltage direct current to the electrodes.

Three-phase machines have advantages over single-phase machines in relation to power factor and maximum kva demand. Power factor is about 40 to 50% for single-phase machines, but because of decreased frequency of the secondary current, is 85% or more for three-phase machines. The kva demand for a three-phase machine is about 50% less than that for a single-phase machine of the same capacity. This demand is distributed over all three phases of the power supply and therefore is further reduced in the ratio of 1.73 to 1, for an over-all reduction of 3½ to 1 — a marked advantage where electric power is limited.

The additional cost of three-phase machines may not be justified where power supply is adequate, or where a large number of machines is involved. Also, a three-phase machine is not generally suitable for welding of thin metal or where weld times of three cycles or less (with 60-cycle current) are required. Three-phase transformers generally have not been applied to multiple-electrode or multiple-transformer machines, because the necessary phase balance can be attained through distribution of single-phase welding transformers over the three phases of the power supply.

Controls for Direct-Energy Machines

Electrical controls for direct-energy resistance welding machines perform three principal functions: (*a*) initiating and terminating the flow of current to the welding transformer, (*b*) controlling the magnitude of the current, and (*c*) timing and controlling the mechanical operations of the welding machine. The controls fall into three groups: welding contactors, timing and sequencing controls, and other current controls and regulators.

Welding contactors are devices for making and breaking an electric power circuit. On resistance welding machines, contactors and other controls are applied to the primary circuit of the welding transformer. A welding contactor should be large enough to handle the maximum input from the electric-power line to the machine with the tap switch at the highest position. Three types of contactors are used on resistance welding machines — mechanical, magnetic and electronic.

Mechanical contactors are of either the single-pole or the double-pole type, and are operated by a foot pedal or a motor-driven cam. In foot-pedal operation, movement of the pedal first applies the squeeze pressure and then closes the electrical contacts. Further movement of the pedal opens the contacts and at the same time increases the welding force.

A magnetic contactor uses an electromagnet for closing the electrical contacts. When the magnet is de-energized, the contacts are opened by gravity and spring pressure. Single-pole, double-pole and synchronously interrupting types of magnetic contactors are available. The synchronously interrupting type opens the power circuit when the alternating-current wave approaches zero, and thus reduces arcing, for longer electrode-tip life and less marking on the work.

Electronic contactors use ignitron tubes, thyratron tubes, or silicon-controlled rectifiers to control the flow of current to the primary winding of the welding transformer. Ignitron tubes are used for applications requiring an extremely high welding-machine current, or a very large number of welding operations per minute. Thyratron tubes or silicon-controlled rectifiers are used to control currents that are too low for ignitron tubes to handle (less than 40 amp).

Electronic contactors, either synchronous or nonsynchronous, always open the circuit when the current wave passes through zero.

An ignitron contactor consists of two ignitron tubes connected in inverse parallel so that one tube carries the positive half-cycle of the welding current and the other tube carries the negative half-cycle.

A schematic diagram of the power-supply circuit and control circuit of an electronic contactor with two ignitron tubes is shown in Fig. 2. Semiconductor-type rectifiers are used to allow current flow from the ignitor to the mercury-pool cathode only. A control-circuit fuse provides protection of the ignitrons and isolation of the control circuit from the power circuit. In machines that are provided with electronic heat control, these rectifiers are replaced by thyratron tubes or by silicon-controlled rectifiers.

An ignitron tube is a rectifier because current flows only from the graphite anode to the mercury-pool cathode. Therefore, two tubes are needed to conduct alternating current. Together, the two tubes act as a single-pole electronic switch to control

*Throughout this article, "per second" has generally been omitted in reference to frequency, and the more familiar "cycle" or "cycles" is used in preference to Hertz (or Hz).

the flow of current to the primary winding of the welding transformer.

Most ignitron tubes are water cooled and have a stainless steel water jacket to prevent corrosion. A thermostatic switch (not shown in Fig. 2) is mounted on one of the tubes to stop operation if the temperature of the tube becomes too high. The other ignitron tube has a thermostatic switch that controls a solenoid-operated water valve, which conserves cooling water.

The contactor energizes the welding circuit when the control circuit is closed. The voltage for the control circuit is obtained from the power-supply circuit. Each ignitron tube is fired for each conducting half-cycle by an ignitor that is energized through the control circuit whenever the control circuit is closed by the timer.

When the duty cycle required of an electronic contactor exceeds the rating of the ignitron tubes, two contactors may be used with an auxiliary control to switch the load alternately from one to the other. When two contactors are operating in this manner, the permissible duty cycle and the averaging time are both doubled. However, the peak load cannot be exceeded, because the entire load at any instant is carried by one contactor only.

Time and Sequence Controls. The duration of current flow to the welding machine is controlled by a welding timer. The over-all operating cycle of the welding machine is timed and controlled by a sequence control or timer. Timing elements are of two types: nonsynchronous and synchronous.

A nonsynchronous timer, by NEMA standards, may start and stop the flow of welding current at random points with respect to the line-current wave form. Variations of timing and of current input to the machine result from closing and opening the welding contactor at random points on the wave form. The time variable is at least plus or minus one half-cycle, and sometimes more. Ordinarily, nonsynchronous timing is sufficiently accurate for weld times of 20 cycles or longer, because the percentage variation is low and can usually be neglected. The nature and quality of the work being done determine the type of timing required for weld times of 10 to 20 cycles. Nonsynchronous timing is not recommended for weld times that are shorter than 10 cycles.

A synchronous timer provides an accurate timing period, and closes the primary circuit of the welding transformer at the same point (electrical angle) with respect to the power-circuit voltage in making each weld. Thus the current wave form is consistent, and the energy delivered to the welding transformer is the same for consecutive operations.

Besides providing accuracy and reproducibility in these respects, a synchronous timer also eliminates variation in initial current caused by load transients. Load transients result from failure to initiate the flow of current at the power-factor angle in the highly inductive secondary circuit of the welding transformer.

A synchronous timer can be used in any application for which a nonsynchronous timer is suitable, but it is more expensive and, to be effective, must be accompanied by heat control.

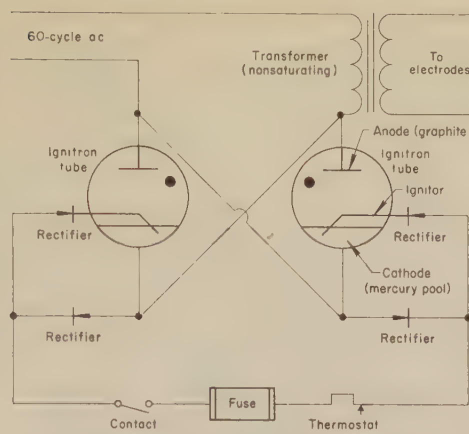


Fig. 2. Diagram of the power-supply circuit and the control circuit of an electronic contactor employing ignitron tubes

Sequence timers are used to control the four basic steps needed for most spot welding cycles. These steps are:

1 Close electrodes and apply force
2 Initiate and maintain welding current
3 Turn off welding current and maintain electrode force until weld nugget solidifies
4 Open electrodes.

The duration of step 1 is referred to as *squeeze time*; of step 2, *weld time*; of step 3, *hold time*; and of step 4, *off time*. Off time is provided by means of a two-position selector switch. One position of the selector switch permits the machine to continue cycling as long as the initiating switch is closed; the other position permits one complete sequence only, after which the machine cannot be restarted until the initiating switch is opened and reclosed.

Heat Control. The tap switch on the primary circuit of the welding transformer is used to change the ratio of transformer turns for major adjustment of the welding current. When an intermediate setting is needed, or for fine adjustment of the welding current, electronic heat control is used. Electronic heat control is standard equipment when synchronous timing controls are employed, and it can be added to nonsynchronous controls.

For electronic heat control, the semiconductor-type rectifiers in an ignitron contactor (see Fig. 2) are replaced as firing devices by thyratrons or silicon-controlled rectifiers. These tubes or rectifiers control firing of the ignitrons during each half-cycle of the welding current. Firing of the ignitron can be delayed by delaying application of a firing signal to the thyratron grid. This delay is usually controlled by a heat-adjustment dial. As the firing of the applied voltage wave is retarded, the root-mean-square (rms) current is reduced. The reduction in heat or energy varies as the square of the applied current, in amperes.

Because ignitron contactors require a certain minimum voltage and current to fire properly, complete control from 100% to zero is not feasible. It is necessary to limit the minimum value to 40% rms current for 220-volt equipment, and to 20% rms current for equipment operating on 440 volts or more. Heat-control switches are calibrated as a percentage of the increment in primary voltage between tap settings.

Automatically controlled phase-shift heat-control circuitry forms the basis of all accessories that change the level of welding current during a welding sequence. Therefore, use of current and voltage regulators, upslope and downslope controls, and quench and temper controls requires that the basic welding-machine control be equipped with a heat-control unit.

To minimize variations in welding current, heat control should be operated as near full heat as possible. Where a welding current of 30% of the maximum rms current is being used, only a few degrees of delay angle will produce a 10% change in welding current. Variations in line voltage can distort the sinusoidal line voltage sufficiently to produce another 10% change at such a low value. Therefore, a tap switch should be used to change the ratio of transformer turns for major changes in current magnitude, and heat control should be used only for fine adjustment of current magnitude.

Power demand is always greater when heat control is used to adjust the magnitude of the welding current. If heat control is used, the kva demand, in relation to maximum, generally follows a linear relationship with current. If the ratio of transformer turns is changed by a tap switch, the kva demand varies as the square of the secondary-current value. For example, if the welding current is adjusted to 80% of maximum by heat control, the kva demand is also 80% of maximum. If the secondary voltage is reduced to 80% of maximum by changing the ratio of transformer turns through a tap switch, the kva demand is about 64% of maximum, or 20% less than when using heat control.

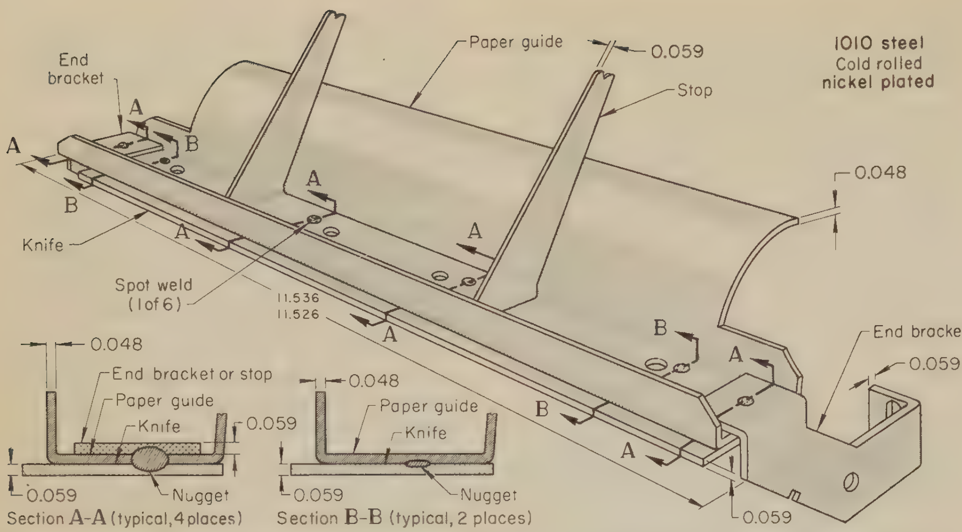
In the following example, in which the welding machine had both a transformer tap switch and phase-shift heat control, two and three thicknesses of metal were spot welded using the same weld-cycle timing but different heat-control settings.

Example 370. Use of Different Heat-Control Settings for Spot Welding Through Two and Three Thicknesses (Fig. 3)

Figure 3 shows a paper-stop assembly consisting of five pieces of nickel-plated cold rolled 1010 steel, which were joined by six spot welds, made one at a time. The over-all length of the assembly was held within ±0.005 in.

As shown in sections A-A and B-B in Fig. 3, four of the spot welds were made through three pieces of metal (total thickness, 0.166 in.), and two were made through two pieces (0.107-in. total thickness). For the three-thickness welds, a heat-control setting of 76% was used, and for the two-thickness welds, 70%. The welding machine was equipped with a phase-shift heat control that was changed manually for the two different heat requirements. The same transformer tap setting was used for both heat-control settings. Indentation at each weld spot was pronounced, but uniform in appearance and smooth. Additional equipment details and welding conditions are given in the table with Fig. 3.

The components were plated (bright nickel, 0.0003 to 0.0005 in. thick) before



Equipment Details	
Power supply	220-v, single-phase ac
Welding machine	Press type
Rating at 50% duty cycle	50 kva
Rating of secondary circuit	1.8 to 6.6 v
Transformer taps	Eight
Electrodes	3⁄16-in. diam, type A (pointed) tip, No. 4 taper, RWMA class 2
Heat control	Phase shift

Welding Conditions	
Welding voltage (est)	4 v
Transformer tap setting	No. 4
Heat-control setting	76% for three thicknesses, 70% for two thicknesses
Electrode pressure	50 psi on 3½-in.-diam air cylinder
Squeeze time	20 cycles
Weld and hold times	10 cycles each
Production per hour	276 welds (46 assemblies)

For the weld through three thicknesses (section A-A), the nugget was typically 0.185 in. in diameter and penetrated about 0.041 in., or 69%, into each of the outer workpieces. For the weld through two thicknesses (section B-B), the nugget was typically 0.130 in. in diameter and penetrated about 0.015 in., or about 31% (based on the thinner material), into each of the workpieces.

Fig. 3. Paper-stop assembly made by joining preplated components with four spot welds through three thicknesses and two spot welds through two thicknesses, using two heat-control settings and the same timing (Example 370)

being spot welded, because when assemblies had been plated after spot welding, chemical solutions were trapped that later bled out and made unsightly stains. All five components were loaded into a fixture, using the edge of the knife as the reference for alignment. Loading and unloading the fixture took 80% of the production time. Although the fixturing was time-consuming, limited demand for this part precluded revision of the design of the part to simplify fixturing and permit more efficient handling.

Upslope control is used for starting the welding current at a low value and controlling its rate of buildup to full welding current. The use of upslope control in resistance spot welding is discussed under the heading "The welding cycle" on page 414, and its application to the single-impulse welding cycle is shown schematically in Fig. 16(b).

Downslope control is used for decreasing the value of the welding current at the end of the welding cycle from the maximum value to a lower value. The use of downslope control in resistance spot welding is discussed under the heading "The welding cycle" on page 414, and its application to the single-impulse welding cycle is shown schematically in Fig. 16(b).

Current and Voltage Regulators. Electronic current regulators are used to maintain a constant welding current under severe conditions by compensating for line-voltage variation or impedance changes resulting from insertion of magnetic materials into the throat of the welding machine. Current regulators provide feedback control of the phase-shift network, based on the primary current.

Voltage regulators designed for use in ordinary welding operations can maintain the welding current within ±2% of its preset operating value for any combination of load-circuit changes that would normally cause unregulated current to change ±20%. The response time of these devices is about 3 cycles at best, and it is recommended that the weld time be a minimum of 6 cycles to allow time for regulation of heat.

Voltage across the welding electrodes can be maintained at a constant preset value by a device that compares the actual electrode voltage with a preset reference voltage and makes automatic corrections in the phase-shift heat control.

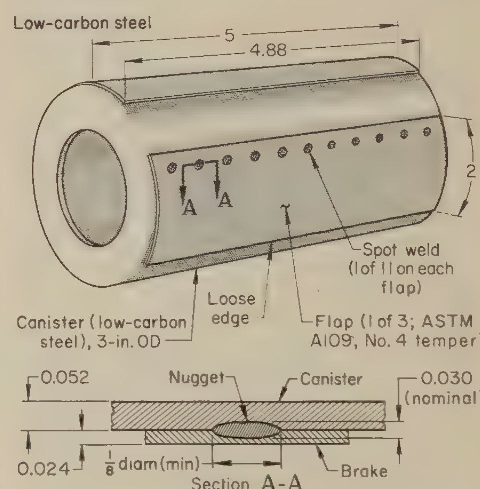
Shunting decreases the current passing through the metal between the electrodes by introducing another path for the welding current, which causes a drop in the welding voltage. A voltage regulator automatically increases the welding voltage when shunting occurs, and thus maintains the correct current level at the weld.

Very large changes in the secondary-current requirements cannot be compensated for by voltage or current regulators, and controls must be reset to provide and maintain suitable welding current at the workpieces. Special in-process feedback control units that automatically adjust the current (phase-shift type) or the timing are sometimes used to compensate for different work-metal thicknesses or number of pieces joined, changes in contour or condition of electrode tips, and changes in work, equipment or ambient conditions that affect welding results.

In the following example, in which double-electrode welding was used to make all but one of an uneven number of spot welds, a separate current-control setting, made by a manually actuated attachment, was used to make the single weld.

Example 371. Change From Single-Electrode to Single-Plus-Double-Electrode Spot Welding With Two Current-Control Settings, To Increase Production Rate and Reduce Costs (Fig. 4)

The low-carbon steel canister shown in Fig. 4 rotated as it was fired from a rifle. To control this rotation, three low-carbon steel flaps (ASTM A109, No. 4 temper) were spot welded to the canister along one edge only. These flaps opened up when the canister left the rifle, and acted as brakes. Initially, the 11 spot welds specified by the purchaser on each flap were welded one at a time, but a faster method for making the welds was needed to meet increased demand. In the improved method, which increased production rate by 66%, a single spot weld was made, followed by five sets of two spots each. To supply the proper current to the electrodes, two current-control settings were needed: one for making the single spot weld, and another for making the ten other spot welds two at a time. Equipment details and welding conditions for the improved method are given in the table with Fig. 4.



Equipment Details	
Power supply	440-v, single-phase, 60-cycle ac
Welding machine	Press type, air operated
Rating at 50% duty cycle	75 kva
Electrodes	Type B (dome), No. 4 taper, RWMA class 2
Fixturing	Indexing and manual(a)

Welding Conditions	Single electrode	Double electrode
Welding current, amp	8800	9000(b)
Electrode force, lb	650	550(b)
Squeeze time, cycles	10	10
Weld time, cycles	15	15
Hold time, cycles	8	8
Production per hour:		
Single-electrode method	3960 welds(c)	
Single-and-double electrode	6600 welds(d)	

(a) Indexing for radial, and manual for longitudinal, location of spot welds. (b) For each electrode. (c) Data are for 120 canisters. (d) Data are for 200 canisters.

In making 11 welds to attach each flap, a single weld was made first, followed by five pairs of welds at a different current-control setting. This method increased production by 66%, and reduced cost by 50%, over original method, in which all 11 welds were made one at a time using a single electrode.

Fig. 4. Canister on which three flaps were spot welded by use of single-and-double-electrode method, with two current-control settings, under conditions in table (Example 371)

In the first process modification, an upper electrode holder that contained two electrodes was used. This holder had a mechanical self-equalizing device designed to provide each electrode with the required working pressure. With this approach, production rate was increased, but it was difficult to maintain an even pressure on the two electrodes simultaneously. The mechanical equalizer was then replaced with two interconnecting hydraulic equalizing adapters. The hydraulic adapters provided the required equalized pressure on the two welding electrodes.

For the single spot weld, a manually operated attachment on the heat control shut off the current to one electrode and adjusted the current now supplied only to the other electrode. After the single spot weld was made, the current control was reset for making the welds two at a time, and welding was completed.

In producing two spot welds simultaneously, electrode maintenance was critical. Consistent production of acceptable weld nuggets of the dimensions shown in section A-A in Fig. 4 was achieved by dressing the electrodes after welding 100 to 200 canisters (3300 to 6600 spot welds), and replacing the electrodes after welding 500 to 600 canisters (16,500 to 19,800 spot welds).

With the original, single-electrode setup, scrap rate was 8% and production rate was 120 canisters per hour. The single-plus-double-electrode procedure decreased the scrap rate to less than 1%, increased production to 200 canisters per hour, and reduced the cost for welding each canister by approximately 50%.

Inspection consisted of a peel test on one flap welded to a scrap canister after completion of each production lot of 30 canisters. Minimum nugget diameter for acceptability of all welds on the test canister was ⅛ in. The location of the flaps on each canister was inspected visually.

Equipment for Direct-Energy Machines

The electrical system of a direct-energy resistance welding machine, shown schematically in Fig. 5, consists of a welding transformer, a tap switch, and the secondary circuit, which includes all the conductors from the transformer secondary terminals to the workpiece. The electrodes are considered here from their electrical standpoint; metallurgical and welding characteristics of electrodes are discussed in subsequent sections in this article.

Controls in the primary circuit are not part of the machine; these are discussed in the preceding section, "Controls for Direct-Energy Machines".

Welding Transformer. The transformer used in a direct-energy resistance welding machine changes the alternating current from high-voltage low-amperage current in the primary winding (or coil) to low-voltage high-amperage current in the secondary winding.

The primary winding is connected to the power supply and is made from edge-bent strip copper, insulated between turns, with the entire coil also thoroughly insulated.

There are three principal arrangements of transformer windings—multistep, series-parallel, and a combination consisting of multistep and series-parallel. The multistep winding consists of one primary coil with one or more intermediate taps to vary the effective number of turns, and thus to change the secondary voltage and current. The number of taps determines the number of different secondary-voltage steps or values that can be furnished by the transformer. The use of eight taps is common and is covered in RWMA standards.

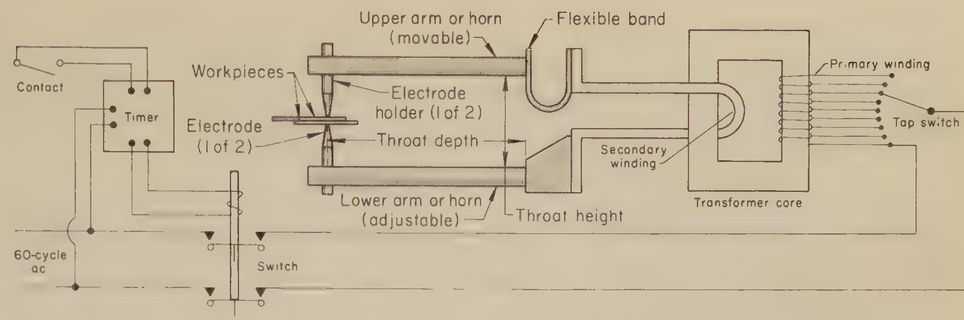


Fig. 5. Diagram of the electrical system of a direct-energy resistance welding machine

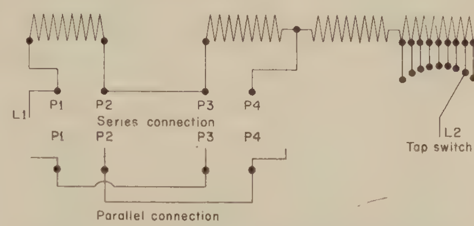


Fig. 6. Connection diagram for primary winding of a series-parallel transformer with an eight-step tap switch

Table 1. Rating Factors for Resistance Welding Machines (RWMA)

Duty cycle, %	Rating factor	Duty cycle, %	Rating factor
1	7.08	30	1.29
2	5.00	35	1.195
3	4.07	40	1.115
5	3.15	50	1.000
7.5	2.57	60	0.912
10	2.23	70	0.843
15	1.82	80	0.787
20	1.58	90	0.745
25	1.41	100	0.707

The series-parallel winding consists of two primary coils that can be connected in series or in parallel. There are no intermediate taps on the coils, and thus this winding provides only two values of secondary voltage. A multistep series-parallel winding results when taps are added to a series-parallel winding. This type of winding provides two different secondary voltages for each transformer tap. Thus, a transformer with a series-parallel winding with eight taps produces 16 secondary-voltage values.

The primary taps are numbered progressively, with the highest open-circuit secondary voltage associated with the highest-numbered tap. In a resistance welding transformer having a series-parallel primary winding, the terminal identification is P1, P2, P3 and P4, as shown schematically in Fig. 6. For series connection, P2 is connected to P3. For parallel connection, the terminals are connected in pairs: P1 is connected to P3, and P2 to P4.

The secondary winding must carry high currents, and therefore has a large cross section. Except in low-capacity equipment, the secondary winding is cooled by circulating water. The primary winding is cooled by conduction to the water-cooled secondary winding.

Transformer ratings for resistance welding machines are expressed in kva (kilovolt-amperes) for a specified duty cycle. Standard practice is to rate resistance welding transformers on a 50% duty cycle. This duty-cycle rating is a thermal rating, and states the amount of power the transformer can deliver for a stated percentage of a time period, usually one minute, without exceeding a specified temperature rise. Thus, a welding machine rated at 100 kva for a 50% duty cycle can deliver 100 kva for 30 seconds of each minute without the transformer components reaching a temperature greater than that for which they were designed. For a repetitive load, one "on" time and one "off" time are considered to be an integrating period, which must not be in excess of one minute.

The kva-demand rating of a welding transformer is the secondary open-circuit voltage multiplied by the secondary (or welding) current, divided by 1000.

The maximum permissible kva demand for a transformer used at a duty cycle other than the one for which the transformer is rated can be calculated from the factors listed in Table 1, in which a 50% duty cycle is assigned a rating factor of 1.000. The maximum kva demand is found by multiplying the rated kva by the factor for the required duty cycle. For example, a 100-kva transformer may be operated at a 25% duty cycle (15 seconds of each minute) at a maximum demand of 141 kva (100×1.41). For a 70% duty cycle (42 seconds of each minute), the maximum permissible demand is 84 kva (100×0.843). The rated kva needed to supply a maximum demand of 90 kva for a duty cycle of 15% (rating factor 1.82) is 90/1.82, or 50 kva.

Tap switches are switching devices for connecting the various taps on the primary winding of the transformer to the power-supply line. The tap setting determines the number of effective turns in the primary winding, and thus the secondary voltage and current. The switches are usually of the rotary dead-front type and are arranged for flush mounting in openings in the machine frame, or directly on the transformer. Most of the switch handles have locking buttons, so that the contacts are centered for each operating position. Some switches have an "off" position, which acts as a disconnect.

On very large transformers, spring contact switches are inadequate and bolted bar jumpers are used.

Tap switches should not be operated with the current flowing, because the resulting arc-over between contacts

will eventually cause damage to the contact surfaces.

The secondary voltage may also be controlled by electronic phase-shift devices. These are discussed in the preceding section, on Controls.

Characteristics of the Direct-Energy Secondary Circuit

The secondary circuit carries the welding current from the transformer to the electrodes, and thus to the workpiece, as shown in Fig. 5. The dimensions of the secondary circuit, or secondary loop, determine to a large extent the output performance of the welding machine. The secondary loop is roughly the area defined by the throat height times the throat depth (see Fig. 5).

Resistance and reactance in the secondary circuit at all points except at the weld should be kept as low as practical, to obtain sufficient welding current with minimum secondary voltage at the lowest possible kva demand on the alternating-current power line.

The materials used in the components of the secondary circuit are selected for low electrical resistivity, and conductors should be large in cross section, but no longer than is necessary. Throat depth and height should be no greater than those needed for the work to be handled.

The relation between throat depth and secondary current (welding current) for spot welding small assemblies of low-carbon steel sheet that do not extend into the throat has been studied for commercial spot welding machines. Some typical results are as follows. At 50 kva power input to the transformer, the welding current when the throat depth was 42 in. was about half that with a throat depth of 12 in. At 75 kva, the welding current with a throat depth of 42 in. was about 70% of that with a throat depth of 12 in.

Considering the results of the study from the viewpoint of the kva demand on the alternating-current power line for a given welding operation, one-third more power was needed to produce a given secondary (welding) current when the throat depth was 42 in. than when it was 18 in. Exact results would vary somewhat, depending on the machine, the work and the welding parameters.

Since magnetic material interposed between the arms or horns of the machine reduces the secondary current in relation to the size and thickness of the material, the extension of steel work metal or fixtures into the secondary loop should be kept to a minimum. An increase in the frequency of the alternating current also reduces the secondary current for a given kva demand.

Machine Construction

On the basis of mechanical construction, there are four basic types of resistance spot welding machines — rocker-arm, press, portable, and multiple-electrode machines.

Rocker-arm machines are the simplest stationary spot welding machines, and are made for use with foot-lever, air-cylinder, or motor operation. The machine, regardless of method of operation, consists of a frame that houses the transformer and tap switch, a vertically adjustable lower horizontal horn, and an upper horn mounted in a rocker arm that is pivoted at the front top edge of the frame.

Rocker-arm machines are available in throat depths of 12 to 48 in. and in transformer capacities of 10 to 300 kva.

Because the upper electrode of a rocker-arm machine moves in an arc, the electrodes should be set in the closed (or welding) position so that the upper electrode is perpendicular to the workpiece and the two horns are parallel. Settings with the horns out of parallel can result in electrode skidding and marking of workpieces.

A foot-operated rocker-arm machine consists of two simple levers connected by a rod and a compression spring. Force exerted on a foot lever is transmitted through the spring to the rocker-arm lever and then to the welding electrode. This machine is best suited for job-shop work with short production runs.

An air-operated machine has an air cylinder that replaces the foot lever, connecting rod, and spring of a foot-operated machine. The stroke of the air cylinder must be proportioned to the needed electrode opening, and the diameter of the cylinder must be proportioned to the needed electrode force and throat depth. For any given cylinder diameter, stroke and operating air pressure, welding force decreases and electrode opening increases as the throat depth of the machine increases, provided the distance between the rocker-arm pivot and cylinder connection is not changed. The welding force provided by any given cylinder is in direct proportion to the air pressure, and is controlled by a pressure regulator.

Air-operated spot welding machines are best suited for short or medium production runs where minimum setup time is needed.

Motor-operated machines are similar to foot-operated machines except that the rocker arm is operated by a power-driven cam instead of by a foot lever. The machine must not be started with the spring solidly compressed, because this can cause the motor to stall. The electrode opening is determined by the rise of the welding cam and by the throat depth. Welding force is dependent on the amount of spring compression and the ratios of leverage involved.

Motor-operated machines are usually more difficult to set up and adjust than foot-operated or air-operated machines, and are best suited for long production runs, or for use where compressed air is at a premium or not available.

Press-type machines have an upper electrode and welding head that move vertically in a straight line. The welding head is guided in bearings or ways of sufficient proportions to withstand the offset loads put on them. These machines have throat depths up to 48 in., and transformer capacities from 5 to 600 kva and greater. Some bench-type models used for radio, instrument, dental and jewelry work have throat depths of only a few inches, and may be rated at less than 5 kva.

Welding force is provided by air or hydraulic cylinders; manual operation is used on small bench-type machines.

Air cylinders are generally used in machines that have welding transformers with capacities up to 300 kva. Hydraulic operation is seldom used in machines with capacities of less than 200 kva, but is used in practically all machines with transformer capacities greater than 500 kva.

Press-type welding machines generally are designed for both spot and projection welding. Tables or platens are provided for mounting dies for projection welding, and fixtures and electrode holders for spot welding. The platens, ram and air or hydraulic cylinder have a common centerline. On standard machines, the spot welding electrodes are mounted six inches in front of this centerline. The knee supporting the lower platen can be vertically adjusted to compensate for reasonable variations in thickness of projection welding dies or in length of spot welding electrodes. For some spot welding applications, the knee can be replaced with an arm or horn to obtain clearance for the workpiece.

Portable machines, or guns, are used in spot welding when it is impractical or inconvenient to bring the work to the machine, and usually consist of four basic units:

1. Portable welding gun
2. Electrical controls such as a welding contactor and a sequence timer
3. Welding transformer
4. Secondary cables and hose needed to carry power between the transformer and the welding gun.

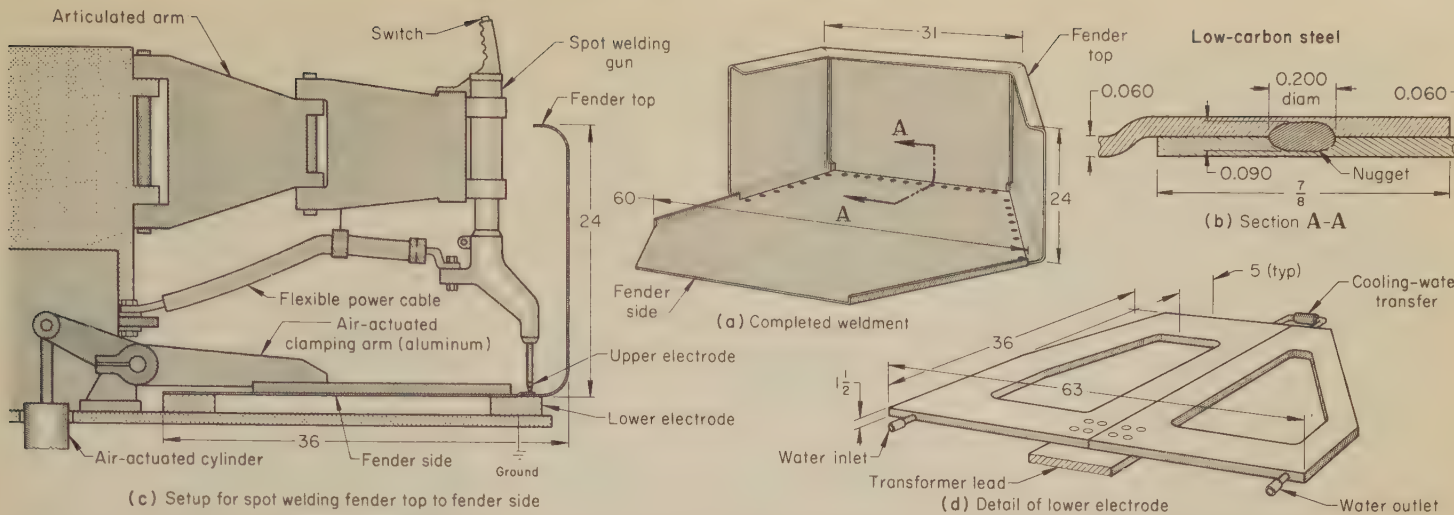
The portable welding gun consists of water-cooled electrode holders, an air or hydraulic actuating cylinder, hand grips, and an initiating switch. The gun usually is suspended from an adjustable balancing unit.

Welding force is supplied by the air or hydraulic cylinder. Hydraulic pressure usually is supplied by an air-hydraulic booster.

Because of the high secondary losses of portable machines, transformers used in these machines have secondary voltage two to four times as great as the voltage of transformers used in stationary machines of equal rating.

The transformer, tap switches, electrical controls, and air-line accessories are mounted on one end of a beam balancer above the work area. On the other end of the beam is a spring balancer that counterbalances the welding gun. The gun has a capacity for vertical movement equal to that of the balancer, and equal to or greater than the reach of the operator. The beam can be rotated 360°, and thus provides an operating area dependent only on the length of the secondary cables.

Welding current is transmitted between the transformer terminals and gun terminals through a secondary cable, usually of the low-impedance or kickless type. The reactance of this type of cable is near zero, which results in a high power factor and reduced kva demand. However, water cooling is necessary. Included with the secondary electric cables are air or hy-



Equipment Details	
Power supply	220-v, 3-phase frequency converter
Welding gun	Heavy-duty, portable, mounted on an articulated arm
Rating at 50% duty cycle	75 kva
Upper electrode	Adapter shank with No. 5 taper, type A (pointed) cap, RWMA class 2
Lower electrode	Casting, RWMA class 2
Welding controls	Synchronous electronic with phase-shift heat control

Welding Conditions	
Heat-control setting	70%
Electrode force	500 lb, max
Squeeze time	15 cycles
Weld time, approx	72 cycles (5 or 6 low-frequency 12-cycle pulses)
Hold time	15 cycles
Production rate(a):	
Fenders per hour	15(b)
Welds per hour	900(b)

(a) With one operator; two had been required for previous method. (b) Production rate in previous method had been 8 fenders (480 welds) per hour.

Fig. 7. Use of a special machine, employing a portable gun, for joining right or left tractor fenders by spot welding a lap joint between side panel and top, under conditions in table. Changing to this method from original method, in which parts were pinned together and welded in a standard press-type spot welding machine, reduced handling and improved weld quality. (Example 372)

draulic pressure hoses, cooling-water hoses, and cable to the initiating switch. This switch is usually operated at low voltage, for reasons of safety.

Current density in low-reactance water-cooled cables is as high as 50,000 amp per 1,000,000 circular mils. Cable sizes are in American Wire Gage (AWG) or thousand circular mils (MCM).

Some types of portable resistance spot welding machines combine the gun and transformer in one portable unit, but these have lower capacity than the separate units described in the preceding paragraphs.

Many large unassembled sheet-metal components without reinforcement are awkward to handle, position and clamp for welding because of their bulk and lack of rigidity, and may require more than one man to manipulate them. When production volume is high enough to justify the capital investment, it may be economical to adapt a portable gun to a special welding machine to allow efficient handling by one man, as in the following example.

Example 372. Use of a Portable Spot Welding Gun in a Special Machine To Improve Weld Quality and Reduce Labor Requirements (Fig. 7)

The tractor-fender assembly illustrated in Fig. 7(a) was made by spot welding a 2-by-5-ft fender top to a 3-by-5-ft side panel. Both components were made from commercial quality low-carbon steel sheet 0.060 in. thick. The lap joint was approximately 5 ft long and required about 60 spot welds spaced 1 in. apart. A section through the spot welded joint is shown in Fig. 7(b).

Originally, the two parts were pinned together through alignment holes in each part, and were welded in a standard press-type spot welding machine. Two men were needed to handle the pinned assembly, and production rate was eight fenders per hour. Weld quality was impaired by warping of the formed sheet-metal fender top during welding. The resulting mismatch and opening of the joint caused changes in the faying-surface contact area, and therefore in the electrical resistance of the workpieces. These changes affected the dimensions of the weld nugget and the strength of the welded joint, and could not be tolerated.

To avoid these difficulties and to allow the job to be performed by one man, a special welding machine was built that incorporated a portable spot welding gun (Fig. 7c). The essential elements of this machine were a clamping fixture that employed an air-actuated aluminum clamping arm, and an articulated arm that carried the portable spot welding gun. A flexible mounting allowed the gun to be moved to any position along the weld line, following a guide (not shown in Fig. 7) attached to the clamping arm.

In operation, insulated pins were passed through the lower electrode and into positioning holes in the side panel and fender top to align the lap joint. The clamping arm was then lowered and held down by an air cylinder, and the welding gun was moved by hand progressively into position for each spot weld along the joint. Once located into position, the welding gun was triggered and the spot weld was completed automatically.

To minimize changes in impedance due to variations in the length of the lower electrode as the welding gun was moved along the joint, the lower electrode was a casting (Fig. 7d) that provided support for the parts along the weld line and a path of fairly uniform resistance for the electrical return to the transformer. The electrode was cast from RWMA class 2 material.

The upper electrode was of RWMA standard cap-and-adapter construction with a No. 5 taper shank. Both cap and adapter were made of class 2 material. The cap was dressed after welding 30 fenders and was replaced about every three days.

Using this welding machine, one man placed the side panel and fender top on the clamping fixture, raised the locating pins, activated the clamping arm, and made the 60 spot welds along the joint. After being welded and unclamped, the fender assembly was removed by the same operator. With this revised production setup, the fender assemblies were completed by one operator at a rate of 15 per hour.

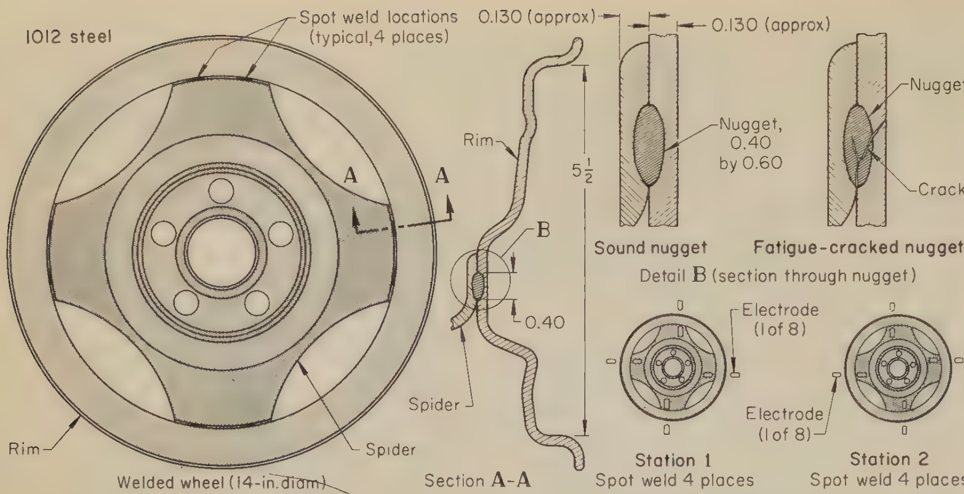
Nondestructive testing of the spot welds was done by attempting to pull the end welds apart manually, and the die side (outer side) of the welded assembly was inspected visually. In addition, test coupons were made and tested to destruction to ensure that the welding-machine settings had not changed. The test coupons used for destructive testing were random samples obtained during production.

The aluminum clamping arms had little effect on the reactance of the machine. Also, the amount of steel in the throat of the machine did not vary enough to affect the resistance or the power factor. These conditions helped in maintaining consistent weld quality.

Power was supplied to the electrodes from a 220-volt three-phase frequency-converter machine with a 50%-duty-cycle rating of 75 kva. Additional equipment details and welding conditions are given in the table that accompanies Fig. 7.

Multiple-electrode machines are considered special-purpose machines, usually designed and built for a specific job. These machines are used when there are so many assemblies to be welded or so many welds per assembly that, even though the machines have a high initial cost, it is more economical to use them than to make the spot welds one at a time. Most of these machines are of the multiple-transformer type, in which each welding gun or pair of guns is connected to an individual transformer and all welds can be made simultaneously, as well as sequentially. Transformers built for such service are provided with two secondaries, enabling each transformer to supply two guns. Often two welds can be made in series, allowing four welds for each transformer.

Guns with 2-in.-diam tandem air cylinders are used for spot welding 0.025-in.-thick cold rolled steel. Tandem cylinders 4 in. in diameter can weld



Equipment Details	
Power supply	440 v, 3-phase
Welding guns	Four at each of two stations
Rating at 50% duty cycle	125 kva per gun
Electrodes	Elliptical, 0.375 by 0.60 in., RWMA class 2
Welding controls	Electronic contactors; phase-shift heat control

Welding Conditions	
Welding current, per spot	19,000 amp, approx
Heating-control setting	30%
Electrode pressure	5000 psi
Weld time	Approx 91 cycles(a)
Production per hour	714 wheels (5712 welds)
Shear strength of welds	Approx 40,000 psi
Fatigue test on welds	1 million cycles(b)

(a) Four heating and three cooling pulses; 12 to 14 cycles each. (b) Minimum, at 150% overload.

Fig. 8. Automotive wheel of which spider and rim were joined with eight spot welds in two four-gun stations of a production line. Service failures by fatigue cracking, as shown at upper right, were rare. (Example 373)

steel up to 0.125 in. thick. Spacing of spot welds is governed by the cylinder diameter. Guns with small-diameter, high-pressure hydraulic cylinders can be used for thicker metal.

The major use of multiple-electrode spot welding machines is in the automobile industry. Multiple spot welding of automotive wheels in a high-volume production line is described in the following example.

Example 373. Use of Two Multiple-Gun Spot Welding Stations in a Production Line, for Making Eight Spot Welds in Wheels (Fig. 8)

In the manufacture of automobile wheels from 1012 steel, the spider was joined to the rim of the wheel with eight spot welds as shown in Fig. 8. The rim, flash welded and contour roll formed as described in Example 445 in the article on Flash Welding, was degreased and dried in an automatic system and conveyed to the assembly end of a production line, where the spider was press fitted into the rim in an assembling press. The outside diameter of the spider was about 0.30 in. greater than the inside diameter of the rim. The spider was flanged, to provide a surface for welding.

The assembly was joined with eight oval-shape spot welds approximately 0.40 by 0.60 in., having a shear strength of about 40,000 psi. The nugget shape and dimensions were selected on the basis of extensive testing, for maximum fatigue life. The 0.60-in. length of each nugget was parallel to the circumference of the wheel, and penetration was typically about 50%. Subsequently, a hole was pierced in the rim for a valve stem and, when specified, the welds were coined on both sides in a ring die to increase their fatigue life.

The production line consisted of a pressing station for assembly, two four-gun spot welding stations capable of applying electrode pressure of approximately 5000 psi during welding, a valve-hole punching station, and a weld-coining station. As shown at lower right in Fig. 8, at the first welding station one spot weld was made in each of the four tabs on the spider, and another spot weld was made in each tab at the second station, for the total of eight welds per wheel. Equipment details and welding conditions are given in the table with Fig. 8.

The completed wheel was visually and mechanically inspected for weld integrity and dimensional accuracy. Wheels were periodically and randomly selected for destructive testing, which was done by placing the wheel in a press and forcing the spider through the rim. This caused the metal to tear out around the eight spot welds, and the size and quality of the welds were easily determined.

The spot welds were fatigue tested to a minimum of one million cycles at 150% overload. Weld failures in service were rare. In a typical failure, as shown at upper right in Fig. 8, fatigue cracks that originated in the weld penetrated to the surface of the rim, causing the wheel to leak air.

Roll spot welding machines are essentially the same as resistance seam welding machines, which are described in the article on Resistance Seam Welding, page 425 in this volume.

The use of a circular seam welding machine for roll spot welding is described in Example 379 in this article.

Function of Electrodes

Electrodes in resistance spot welding perform three major functions:

1 Conducting the welding current to the workpieces
2 Transmitting to the workpieces in the weld area the amount of force needed to produce a satisfactory weld
3 Rapidly dissipating the heat from the weld zone.

During the welding operation the electrodes are subject to great compressive stresses at elevated temperature, and must be frequently dressed and periodically replaced. Because the current conducted to the workpieces must remain localized within a fixed area, the electrodes must resist these stresses without excessive deformation. The electrode force, in addition to forging the heated workpieces together, influences the passage of current to the localized area (see the section on Effect of Welding Force on Heating, page 413).

Maintenance of Electrodes. The shape, dimensions and surface condition of the electrode tips or contact surfaces are important for consistent weld quality in resistance spot welding. Shape and dimensions of electrode tips are affected by mechanical wear and deformation or "mushrooming", at a rate depending on tip material and design, operating temperatures, rates of heating and cooling (thermal shock), and welding force.

Alloying between the electrode tip and the work metal can greatly increase the rate of deterioration of the electrode tip. Deterioration is especially rapid when copper alloy electrodes are used in welding work metal coated with tin, zinc or aluminum, which alloy readily with the electrode metal.

Careful attention to electrode-tip condition is needed in order to avoid such defects as weak or missed welds, irregularly shaped welds, erratic indentation, burning or discoloration of the work surface, surface melting, and electrode deposits on the work surface. Electrode tips should be dressed and replaced at scheduled intervals.

Programs of preventive electrode maintenance are described in Examples 371 and 377; the program should be developed to meet the specific needs of the individual welding facility or plant. Preventive maintenance is particularly important when multiple-electrode holders are used, to ensure uniformity of resistance at each spot.

Electrode Materials

Materials for spot welding electrodes should have sufficiently high thermal and electrical conductivities, and sufficiently low contact resistance, to prevent burning of the workpiece surface or alloying of the electrode face with it, and should have adequate strength to resist deformation at operating pressures and temperatures. Because that part of the electrode that contacts the workpiece becomes heated to high temperatures during welding, hardness and annealing temperature must also be considered.

Electrode materials have been classified by RWMA into two composition groups — copper-base alloys and refractory-metal compositions. These classifications cover a wide range of resistance welding electrode materials to meet most applications.

Copper-Base Alloys (RWMA Group A). Table 2 gives the minimum properties for copper-base alloys (RWMA group A) used as electrode materials for resistance spot welding of steel. This group includes classes 1, 2 and 3.

Class 1 material is a copper-base alloy having a nominal composition of 1% cadmium and 99% copper. It has high strength and hardness coupled with high electrical and thermal conductivities. Class 1 material is non-heat-treatable, and is strengthened and hardened by cold working, which does not affect the high electrical and thermal conductivity. Class 1 material is recommended for spot welding of low-carbon steel coated with tin, terne metal, chromium or zinc; scaly hot rolled

Table 2. Minimum Properties for RWMA Group A, Classes 1, 2 and 3, Electrode Materials (Copper-Base) (a)

Diameter or thickness of electrode material, in.	Proportional limit, tension, psi			Rockwell B hardness			Electrical conductivity, % IACS(b)			Tensile strength, psi			Elongation in 2 in.(c), %		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Round Rod Stock															
Up to 1-in. diam	17,500	35,000	50,000	65	75	90	80	75	45	60,000	65,000	100,000	13	13	9
1 to 2-in. diam	15,000	30,000	50,000	60	70	90	80	75	45	55,000	59,000	100,000	14	13	9
2 to 3-in. diam	15,000	25,000	50,000	55	65	90	80	75	45	50,000	55,000	95,000	15	13	9
Square, Rectangular and Hexagonal Bar Stock															
Up to 1 in. thick	20,000	35,000	50,000	55	70	90	80	75	45	60,000	65,000	100,000	13	13	9
Over 1 in. thick	15,000	25,000	50,000	50	65	90	80	75	45	50,000	55,000	100,000	14	13	9
Forgings															
Up to 1 in. thick	20,000	22,000(d)	50,000	55	65	90	80	75	45	45,000	55,000	94,000	12	13	9
1 to 2 in. thick	15,000	21,000(d)	50,000	50	65	90	80	75	45	40,000	55,000	94,000	13	13	9
Over 2 in. thick	15,000	20,000(d)	50,000	50	65	90	80	75	45	40,000	55,000	94,000	13	13	9
Castings															
All	...	20,000	45,000	..	55	90	..	70	45	...	45,000	85,000	..	12	5

Source: "Resistance Welding Equipment Standards", American National Standard C-88.2, ANSI, New York, 1969

(a) Nominal compositions: class 1, 1% cadmium, rem copper; class 2, 0.8% chromium, rem copper; and class 3, 0.5% beryllium, 1.0% nickel and/or 1.0% cobalt, rem copper. (b) International Annealed Copper Standard. (c) Or in a length equal to four times the diameter of the test specimen. (d) For hot worked and heat treated (but not cold worked) electrode material.

low-carbon steel; and some nonferrous metals, such as aluminum and magnesium alloys. It is available as drawn rod and bar, forgings, strip and plate.

Class 2 material is a copper-base alloy having a nominal composition of 0.8% chromium, remainder copper, and has higher mechanical properties but lower electrical and thermal conductivities than those of class 1 material. Optimum mechanical and physical properties are developed by heat treatment or by a combination of heat treatment and cold working. Class 2 material is the best general-purpose electrode material and can be used with a wide range of metals and conditions.

Class 2 material is used in electrodes for spot welding of cold rolled low-carbon steel, hot rolled pickled low-carbon steel, nickel-plated steel, stainless steel, nickel alloys, and copper-base alloys such as silicon bronze and nickel silver. It is also suitable for shafts, arms, dies, fixtures, platens, gun jaws and other current-carrying structural members of resistance welding equipment. It is available as drawn rod and bar, strip stock, plate, castings and forgings. Class 2 electrodes were used in all examples in this article for which the electrode material was identified.

Class 3 material is a copper-base alloy having a nominal composition of 0.5% beryllium, 1.0% nickel (sometimes omitted), 1.0% cobalt, remainder copper. It is a hardenable alloy with higher mechanical properties but lower electrical and thermal conductivities than those of either class 1 or class 2 materials.

The high hardness, good wear resistance and high annealing temperature of class 3 material, coupled with medium electrical conductivity (45 to 50% IACS), make it a good material for electrodes used in spot welding applications where pressures and workpiece resistance are high. It is used on thick sections of low-carbon steel, and on such materials as stainless steel, Monel and Inconel.

Class 3 material is available as drawn bar and rod, strip, castings and forgings.

Refractory-Metal Compositions (RWMA Group B). Table 3 gives minimum properties for refractory-metal compositions (RWMA group B) used as electrode materials for resistance spot welding of steel. This group includes classes 10 through 14.

These electrode materials are used where high heat, long weld time, inadequate cooling or high pressure would cause rapid deterioration of the copper-base alloys. In choosing among them, each application must be considered separately on the basis of design of electrode and workpieces, type of opposing electrode and type of spot

Table 3. Minimum Properties for RWMA Group B Electrode Materials (Refractory-Metal Compositions) (a)

Class	Rockwell hardness	Electrical conductivity, % IACS(c)	Compressive strength, psi
10	B 72	35	135,000
11	B 94	28	160,000
12	B 98	27	170,000
13	A 69	30	200,000
14	B 85	30	...

(a) Properties are for rods, bars and inserts. Classes 10, 11 and 12 are copper-tungsten mixtures; class 13 is unalloyed tungsten; and class 14 is unalloyed molybdenum. (c) International Annealed Copper Standard. [Source of table: Same as that for Table 2]

welding equipment. When a copper alloy is being welded to steel, a group B electrode is used to contact the copper alloy, and a group A electrode of class 1 or 2 is used to contact the steel.

Class 10 material is a high-melting-point copper-tungsten refractory metal recommended for use in facings on spot welding electrodes for applications requiring a compromise between the high electrical and thermal conductivities of the copper-base alloys and the high hardness and strength provided by the other refractory-metal compositions.

Class 11 material is a 42% copper, 58% tungsten (by volume) refractory metal with a higher hardness but lower electrical conductivity than those of class 10 material. It is specially recommended for spot welding of ferrous metals having high electrical resistance, such as stainless steel. (Class 11 insert buttons were selected in Example 374.)

Class 12 material is a copper-tungsten refractory metal that has higher hardness and lower electrical conductivity than those of class 11 material.

Classes 13 and 14 materials consist of unalloyed tungsten and unalloyed molybdenum, respectively. Their properties are not usually needed in resistance spot welding of low-carbon steel, except for joining it to such metals as copper alloys. (Class 13 was an optional material in Example 374.)

Special alloys, such as copper-zirconium and copper-cadmium-zirconium, have properties similar to class 1 and class 2 materials and have been used as resistance welding electrodes. They are suitable for spot welding of steel coated or plated with metals such as zinc, aluminum, tin, terne metal and cadmium, and for spot welding of aluminum and magnesium alloys.

In any application where a class 1 material can be used, a copper-zirconium alloy can be used if increased resistance to annealing (or softening) of the electrode face is needed.

Electrode Design

Electrode design involves four structural features of the electrode: face; shank or body; means of attachment to the electrode holder; and provision for cooling (see Fig. 9).

The face of a spot welding electrode contacts the workpiece directly above or below the point of fusion, and this small area is subject to repeated application of high temperature and pres-

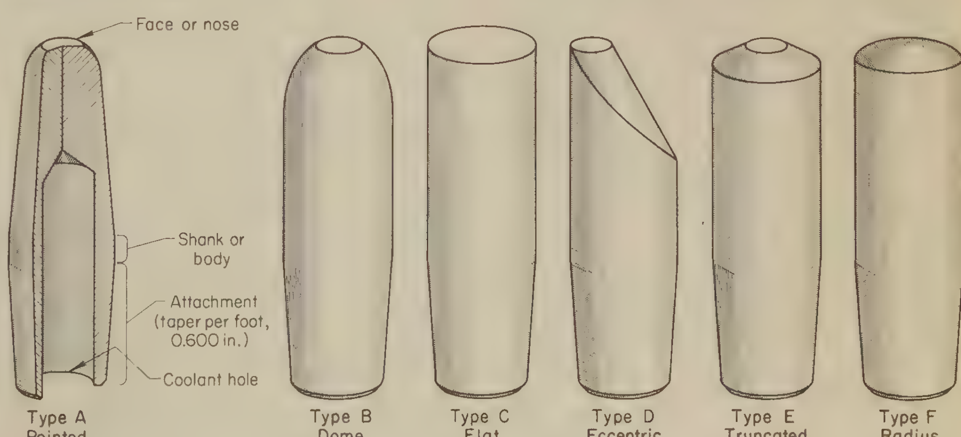


Fig. 9. Standard types of electrode face or nose shapes. (Type D was formerly called offset.)

sure in production welding; therefore, the probability of pickup, alloying and deformation is a major consideration in electrode design. In minimizing pickup or alloying of the work metal and electrode material, the affinity of one for the other is important. Resistance to deformation depends on the hardness and strength of the electrode material. In choosing the electrode material that will produce the best results, a compromise between properties is frequently necessary. The size and shape of the electrode tip sometimes can be modified to compensate for compromises in electrode material.

Dimensions of the electrode face are governed by thickness of the work metal, desired size of the weld nugget, and shape and size of the assembly.

Electrode face shapes have been standardized by RWMA; Fig. 9 shows the six standard face or nose shapes, identified by letters A through F. Electrodes with type A (pointed) tips are used in applications for which full-diameter tips are too wide. Type D (eccentric; formerly called offset) faces are used in corners or close to upturned flanges. Special tools are available for dressing electrode faces, either in or out of the welding machine.

Shank ends or attachments of standard RWMA electrodes are made with Jarno tapers 3, 4, 5, 6 and 7. Body diameters are equal to the Jarno taper number divided by eight (3/8, 1/2, 5/8, 3/4 and 7/8 in.). Some manufacturers continue to follow an earlier standard, and use the Morse taper numbers 1, 2 and 3, which are essentially the same as RWMA (Jarno) tapers 4, 5 and 7.

Coolant holes in electrodes are either round or fluted. Fluted holes offer more cooling surface than do round holes. Coolant holes should extent as close to the face of the electrode as possible, without endangering electrode strength.

The electrode designs shown in Fig. 9 cannot be used for all applications. Also available are electrodes having the shape of buttons about 3/16 in. high, and electrodes with single-bend and double-bend offsets, irregular offsets, square or rectangular faces, and caps with male or female tapers or threads.

Buttons and caps of various nose designs, which are used with special adapter shanks that are placed in standard holders, are interchangeable in their respective adapters.

The diameter of the tip or contact face of the electrode controls the size of the weld nugget. If the diameter of the tip is too small, the resulting spot weld may be weak, even though it is sound. Small-diameter tips also may cause severe heat concentration and surface marking or indentation.

Electrodes with large-diameter faces may overheat because of insufficient electrode pressure, especially at high welding current, and cause voids, blowholes, or a poor surface appearance.

The minimum face diameter for type A, B, D and E electrodes can be determined by using the following formula:

$$\text{Face diameter, in.} = 0.10 + 2t$$

where t is the thickness, in inches, of the base metal contacting the electrode.

RWMA Designation Code. For identification of straight group A (copper-base alloy) electrodes, RWMA has established four-part code numbers:

1. A letter, A through F, that indicates the type of face (see Fig. 9)
2. A number from 1 through 5 that indicates the RWMA class of electrode material
3. A number from 3 through 7 that designates the RWMA (Jarno) taper of the shank end and, when divided by 8, indicates nominal body diameter
4. A two-digit number that indicates the length of the electrode in increments of 1/4 in.

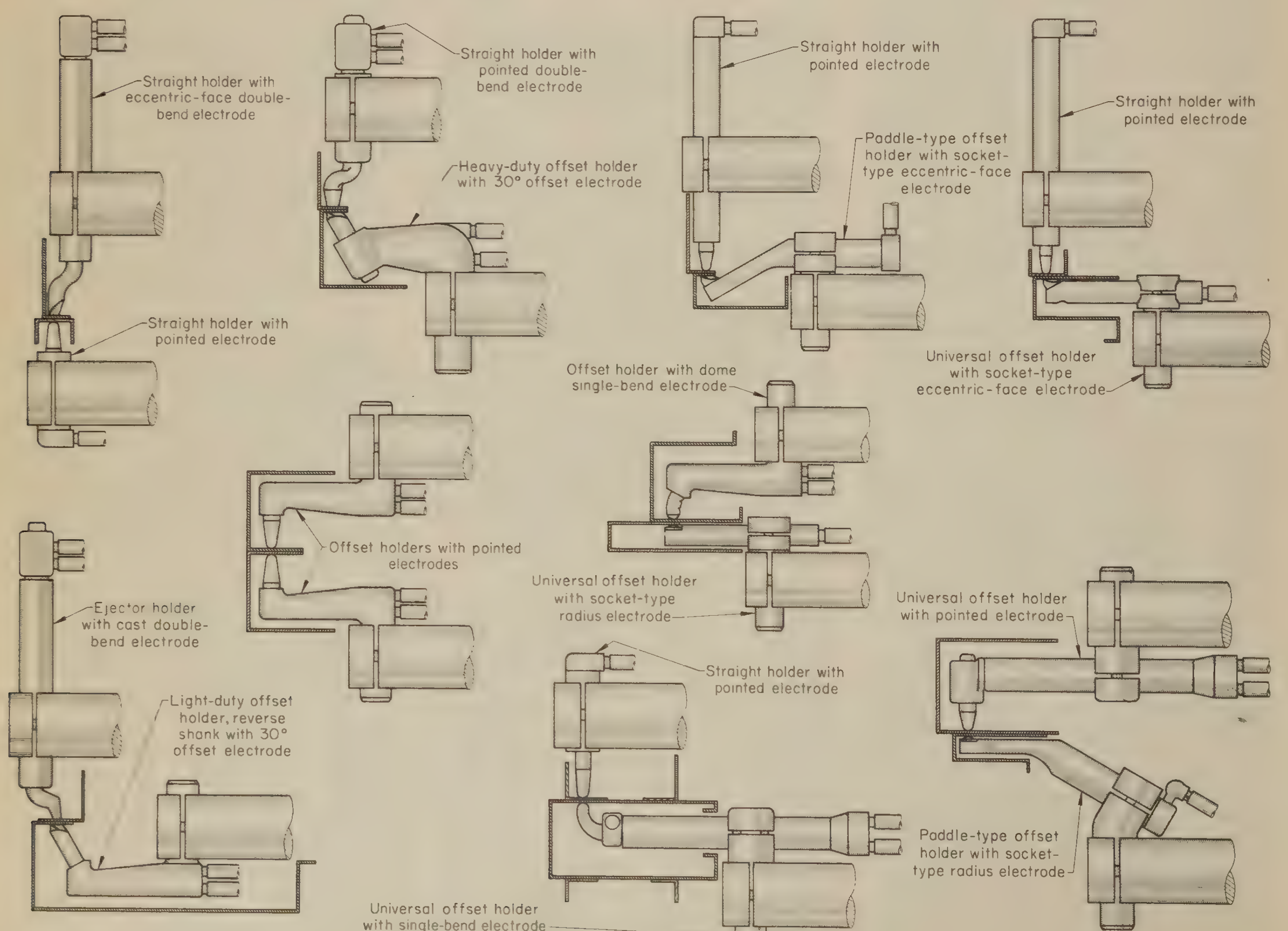


Fig. 10. Combinations of standard holders, adapters and electrodes for resistance spot welding with various workpiece configurations

Thus, an electrode having an RWMA code number A-2516 has a type A (pointed) face, is made of class 2 material, has a No. 5 RWMA taper on the shank end and a ⅝-in.-diam body, and is 4 in. long.

No designation code of this type has been established for group B (refractory-metal) electrodes, since these electrodes are used as facings, inserts, buttons or other nonstandard forms.

Electrode Holders

In resistance spot welding, electrodes are placed in holders that are mounted in the machine so that the position of the electrode can be adjusted to suit the workpieces. Most holders have an ejector mechanism for removing the electrodes and have hose connections to provide water cooling. Holders are made in straight and offset designs for taper-shank and threaded-shank electrodes or adapters, and for button-type and cap-type electrodes.

Holders for taper-shank electrodes may either be straight or have 90° or 30° offsets. Most holders for threaded-shank electrodes are straight but have 90° and 30° adapters. Universal and paddle-type holders have a relatively long, thin extension into which button-type electrodes are inserted.

Some combinations of standard holders, adapters and electrodes that permit the handling of various workpiece configurations and joint arrangements are shown in Fig. 10.

Multiple-electrode holders are used for simultaneously making two or more spot welds in an assembly, using conventional spot welding machines. These holders, which are generally used for the upper electrodes, have springs, mechanical devices, or hydraulic equalizers so that the same force is applied to the workpiece by each electrode. Equal electrode force for each spot weld helps to maintain uniform weld quality. The electrodes can be connected to the transformer in different arrangements for direct or series spot welding (see Fig. 13 for typical arrangements of transformer secondary circuits).

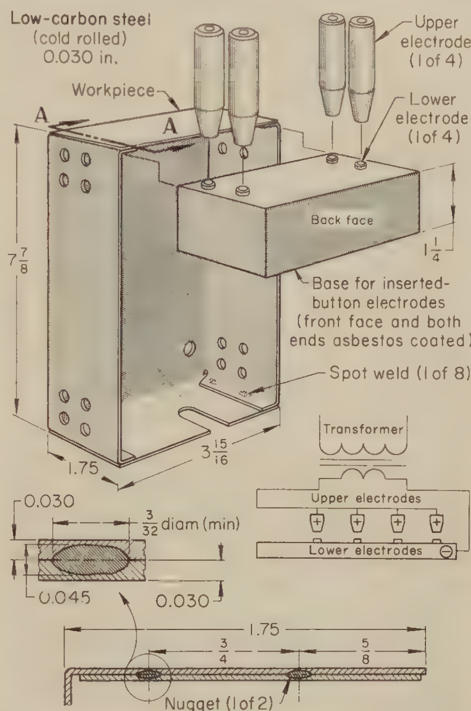
The lower electrode may be a solid piece of metal large enough to oppose all the upper electrodes, or a solid piece of metal with inserts positioned opposite to the upper electrodes, or it may consist of individual tips mounted in a fixed holder. Provision must be made for the necessary electrical connection of the electrodes to the machine, and for adequate water cooling.

In the next example, electrodes and electrode holders were designed to enable four parallel spot welds to be made simultaneously in the end of a low-carbon steel box by direct welding. Similar setups were used to make three to six welds at a spacing of 4 in. (max) on copper alloys and stainless steels.

Example 374. Use of Multiple-Electrode Holders To Make Four Spot Welds Simultaneously (Fig. 11)

Folded boxes (open-top containers) like the one shown in Fig. 11 were made of 0.030-in.-thick cold rolled low-carbon steel by forming the sides and ends in a press or a press brake, and then spot welding the corners. On each end of the box four spot welds (two parallel pairs) were made simultaneously, using specially designed electrodes and electrode holders.

The upper electrode holder was mounted in a spring-counterbalanced head that provided a low-inertia reaction as the work metal was heated and the spot weld was formed. The upper electrodes were mounted in a spring-loaded equalizer, so that each electrode exerted a force of about 180 lb on the workpiece. The base, or holder, for the four inserted-button lower electrodes was offset ahead of the horn so that the box would not touch the horn in the welding position. Also, the front face and both ends of the lower-electrode base were covered with a thin coating of asbestos cement to insulate them from the box during welding, and to prevent shunting.



Equipment Details

Welding machine	Bench mounted, press type, single-phase
Rating at 50% duty cycle	30 kva
Current, max	14,000 amp
Transformer taps	Eight
Upper electrodes (4)	Type A (pointed), ¼-in. diam, RWMA class 2
Lower electrodes (4)	Button type, ¼-in. diam with $\frac{1}{32}$ by 45° chamfer, RWMA class 11 or 13, mounted in a class 2 base
Heat control	8 taps and phase shift

Welding Conditions

Welding current (total for 4 spots)	6000 amp
Transformer tap setting	No. 6
Heat-control setting	60%
Electrode force	180 lb per electrode
Squeeze time	2 cycles
Weld time	4 to 5 cycles
Hold time	2 cycles
Production per hour	640 welds (80 boxes)

Fig. 11. Folded box in which four spot welds were made simultaneously in each end, by direct welding with a multiple-electrode holder (Example 374)

The upper electrodes were made of RWMA class 2 material. The lower electrodes were insert buttons made of either class 11 (copper-tungsten) or class 13 (tungsten) material, and were mounted in a class 2 base. The selection of copper-tungsten electrode buttons permitted the use of lower welding current and electrode force than are normally recommended for welding low-carbon steel, and reduced wear on the buttons.

The electrode design was developed experimentally, and the electrodes were carefully machined to close dimensional tolerances. The electrode force was carefully balanced to give equal loading to all spots, and the electrodes were dressed frequently to give uniform contact at all spots.

The welds had a minimum diameter of $\frac{3}{32}$ in. and had adequate strength for the low stress to which they were subjected in use. Equipment details and welding conditions are given in the table with Fig. 11.

Direct and Series (Indirect) Welding

The arrangement of the electrodes and workpieces in the secondary circuit in resistance spot welding determines whether welding is direct or series (indirect). Welding is direct if all of the secondary current passes through the weld nugget (or nuggets) being formed, so that no effective shunt path bypasses the nugget. Welding is series (also called indirect) if there is a shunt path that allows a portion of the secondary current to bypass the weld nugget. Some arrangements of secondary circuits for direct and series welding of two thicknesses of metal are described below; in general, these arrangements also apply for welding of three or more thicknesses.

Direct Single-Spot Welding. Single spot welds are usually made by direct welding. Figure 12 shows schematically three arrangements used for making this type of weld; these arrangements may be modified to meet special requirements. In all of the arrangements shown, one transformer secondary circuit makes one spot weld.

The simplest and most common arrangement, in which two workpieces are sandwiched between opposing upper and lower electrodes, is shown in Fig. 12(a). In the arrangement shown in Fig. 12(b), a conductive plate or mandrel having a large contacting surface is used as the lower electrode; this reduces marking on the lower workpiece and conducts heat away from the weld more rapidly, and may be necessary because of the shape of the workpiece. In the arrangement in Fig. 12(c), a conductive plate or mandrel beneath the lower workpiece is

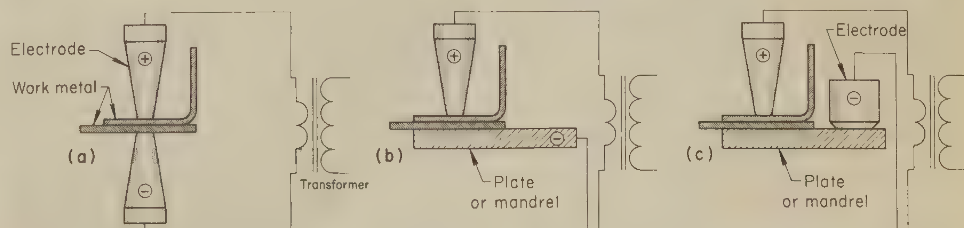


Fig. 12. Three arrangements of work metal and electrodes used for making single spot welds by direct welding

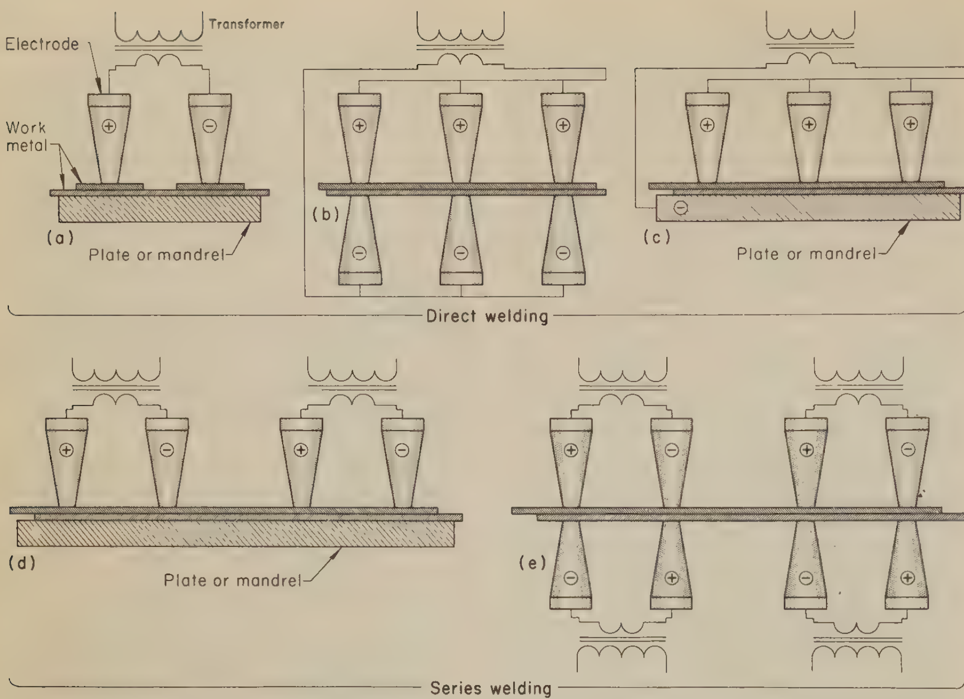


Fig. 13. Five arrangements of work metal and electrodes used for making multiple spot welds simultaneously by direct and series welding, using one or more secondary circuits

used for the same purposes, but in conjunction with a second upper electrode. Because this second upper electrode is intended to serve as a contact only and not to make a weld, it may be larger (as shown in Fig. 12c) to avoid overheating.

Direct Multiple-Spot Welding. Three arrangements of the secondary circuit for making two or more spot welds simultaneously by direct welding are shown schematically in Fig. 13(a), (b) and (c). One transformer secondary circuit can be arranged as shown in Fig. 13(a) to make two spot welds, joining two upper workpieces to one lower workpiece. In this application, the plate or mandrel need not be an electrical conductor.

A single transformer secondary circuit can also be arranged as shown in Fig. 13(b) and (c) to make two, three or more spot welds simultaneously by direct welding, joining two workpieces. Special care must be taken in this method (sometimes called parallel spot welding) to ensure that resistance (impedance) in the circuit for each spot weld is the same as for all the others; otherwise, current will not be uniform for each weld. Tip contour and surface condition must be the same for each electrode. Also, the force exerted by all the electrodes on the workpieces must be equal, regardless of inequalities in work-metal thickness. The force can be equalized by using a spring-loaded electrode holder or a hydraulic equalizing system.

The use of a conductive plate or mandrel, as in Fig. 13(c), minimizes weld marks on the lower workpiece.

Series Multiple-Spot Welding. Two arrangements for making a number of spot welds simultaneously by series welding are shown schematically in Fig. 13(d) and (e). In Fig. 13(d), each of the two transformer secondary circuits makes two spot welds. A portion of the current bypasses the weld nuggets through the upper workpiece. Four spot welds are conveniently made simultaneously in this way, using the two separate secondary circuits of a standard "package" type of resistance welding transformer. Several transformers of this type can be combined to make a larger number of spot welds simultaneously, or one of the two secondary circuits can be used alone to make just two welds at a time.

Figure 13(e) shows the arrangement for push-pull, or over-and-under, series multiple-spot welding. In this arrangement, each weld is made between a pair of opposing electrodes of opposite polarity, with each electrode being connected to a separate transformer secondary winding, and only one weld is produced for each secondary circuit. This arrangement provides a relatively high voltage at the welds, because the voltages of the two secondary windings for each pair of spot welds reinforce each other. This arrangement also permits the use of transformers having lower kva ratings than can be used with the arrangement shown in Fig. 13(d), but care is needed to limit shunting to an acceptable amount.

Heat for Resistance Welding

The secondary circuit of a resistance spot welding machine, including the work being welded, is a series of resistances, the total of which affects the flow of current. The current flow (in amperes) must be the same in all parts of the circuit, regardless of the resistance at any point; however, the heat generated at any point is directly proportional to the resistance at that point. Electrical systems in the secondary circuit are designed to produce heat where it is wanted, leaving the other components of the circuit relatively cool.

The composite effects of heat generation and dissipation in the workpieces and electrodes are shown in Fig. 14. There are seven resistances connected in series for a two-thickness joint: (*a*) the upper electrode, (*b*) the contact surface between the upper electrode and upper workpiece, (*c*) the upper workpiece, (*d*) the contact surface between the upper and lower workpieces, (*e*) the lower workpiece, (*f*) the contact surface between the lower workpiece and lower electrode, and (*g*) the lower electrode.

Heat is generated at each of these points in proportion to the resistance at that point. The greatest amount of heat is desired at the weld point or interface between the workpieces (point *d* in Fig. 14), and steps must be taken to reduce the heat as much as possible at the other points.

The temperature of all parts at the start of the weld is represented by the line marked "Starting temperature" in Fig. 14. Temperature is rapidly increased at point *d*, the interface between the workpieces, where the resistance is greatest. Points of next greatest resistance are *b* and *f*, where the temperature rises rapidly, but not as fast as at *d*. The heat generated at points *b* and *f* is rapidly dissipated into the water-cooled electrodes at points *a* and *g*, whereas the heat generated at point *d* is dissipated much more slowly.

After about 20% of the weld time has elapsed, the heat gradient corresponds to the inner curve in Fig. 14. The outer curve represents the heat gradient at the end of the weld time (100% of weld time). When welding conditions are properly controlled, the welding temperature is first reached at sites near *d*, the interface between workpieces. During the heating period, these tiny regions of molten metal enlarge and become continuous, to form the weld nugget.

The temperature gradients shown in Fig. 14 are also affected by the relative thermal conductivities of work metal and electrodes, and by the size, shape and cooling rate of the electrodes (explained in the next sections).

Effect of Welding Current on Heating

Welding current flows through a secondary circuit that consists of the transformer secondary coil, the flexible bands connecting the coil to the horns, the horns, the electrodes, and the workpiece. Heat is generated in all portions of the circuit according to the following formula:

$$H = I^2Rt$$

where H is the heat in watt-seconds or joules; I is the current in amperes; R is the resistance in ohms; and t is the duration of current flow in seconds. Some heat is lost through conduction, convection and radiation from the electrodes and the workpieces. Generally, the magnitudes of these losses are unknown.

The thermal conductivity of steel is about 12% that of copper; therefore, if sufficient welding current is used in

welding steel with copper-base electrodes, the heat generated along the interface of the workpieces (point *d* in Fig. 14) is conducted away from the weld zone more slowly than the heat generated at the electrode faces (points *b* and *f* in Fig. 14) is conducted into the water-cooled electrodes (points *a* and *g* in Fig. 14). Thus, the interface of the workpieces reaches the fusion temperature first, and a weld is produced at this interface.

There is a lower limit for current density below which fusion cannot be obtained. Enough heat must be generated to offset the heat that is lost through conduction into the electrodes, surrounding air, and that part of the work metal not between the electrodes.

As the current density is increased, the weld time can be decreased sufficiently to produce a weld without heating the electrode contact surfaces to more than a few hundred degrees.

There is also an upper limit for the welding current. If the welding current is too high, the entire thickness of the work metal between the electrodes is heated to the plastic range by the time the weld zone reaches the fusion temperature, and the electrodes embed themselves deeply into the metal. The outer surfaces of the electrodes may also be overheated and burned.

For a given electrode force, there is an upper limit of current density above which pitting and expulsion of hot metal occur at one or more workpiece surfaces, causing low-quality welds. Maximum spot strength is obtained by welding at a current density slightly below the value at which expulsion takes place (setting of the current for production runs is commonly based on this relation).

The effects of welding current on nugget diameter, joint tensile-shear strength, and electrode indentation are shown in Fig. 15. The welds were made in annealed low-carbon steel, 0.029 in. thick, using a type A (pointed) electrode with a ¼-in.-diam tip, an electrode pressure of 15,000 psi (a force of about 735 lb), and a weld time of 6 cycles. At the optimum current value (13,500 amp), the diameter of the nugget was nearly the same as the diameter of the electrode tip (¼ in.). Increasing the current above 13,500 amp did not significantly increase the nugget diameter, but caused a marked increase in electrode indentation. Tensile-shear strength increased rapidly until the optimum current was reached, but decreased slightly when the current was increased to slightly above 14,000 amp. Indentation increased from about 2% of the sheet thickness at a welding current of 13,500 amp to about 10% at a welding current slightly above 14,000 amp.

Effect of Electrode Composition and Design on Heating

Electrodes should have high electrical conductivity and low contact resistance to minimize electrode heating, and high thermal conductivity to dissipate the heat from the contact area between the electrode tip and the workpiece (zones *b* and *f* in Fig. 14).

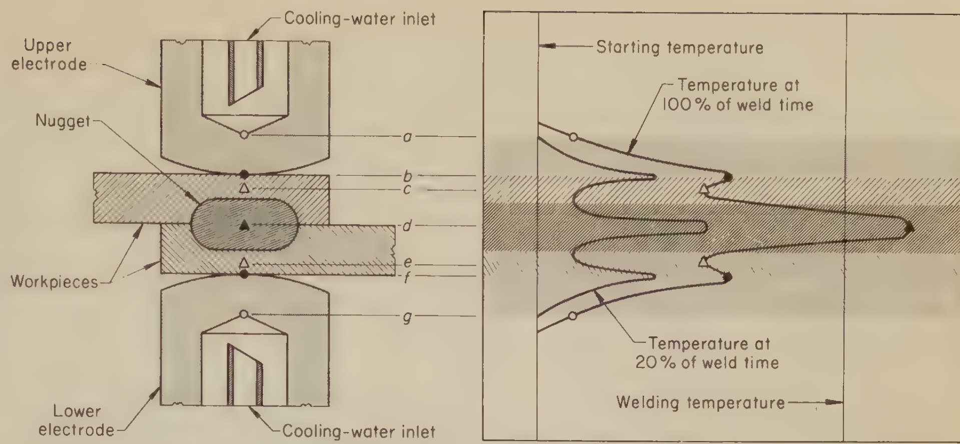
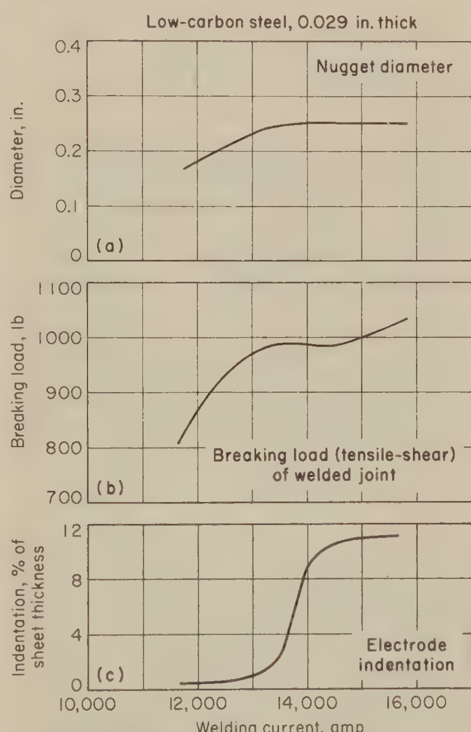


Fig. 14. Major points of heat generation, and temperature gradients after 20% and 100% of weld time, in electrodes, workpieces, and nugget during formation of a resistance spot weld



Electrode had a type A (pointed) face, ¼-in.-diam tip; electrode pressure was 15,000 psi; weld time was 6 cycles. (SOURCE: RWMA Resistance Welding Manual, 3rd Ed., Vol 1, p 122)

Fig. 15. Effects of welding current on nugget diameter, joint tensile-shear strength, and electrode indentation, in spot welding of annealed low-carbon steel 0.029 in. thick

Electrodes should also be strong enough to resist deformation caused by repeated applications of high welding force.

Effect of Electrode Composition. Generally, the harder an alloy is, the greater is its thermal and electrical resistance, and in choosing the best alloy for electrodes, a suitable compromise among electrical, thermal and mechanical properties must be found.

Commercially pure copper has excellent electrical conductivity, but because of its low resistance to compressive forces and low annealing temperature, it has been replaced by other copper-base alloys as an electrode material. The copper-base alloys that have been adopted as standard materials for resistance spot welding electrodes (RWMA group A, classes 1, 2 and 3) are described on page 408, and minimum properties for these standard electrode materials appear in Table 2.

Standard refractory-metal compositions for resistance spot welding electrodes (RWMA group B, classes 10 to 14) are described on page 409, and minimum properties for these materials are given in Table 3.

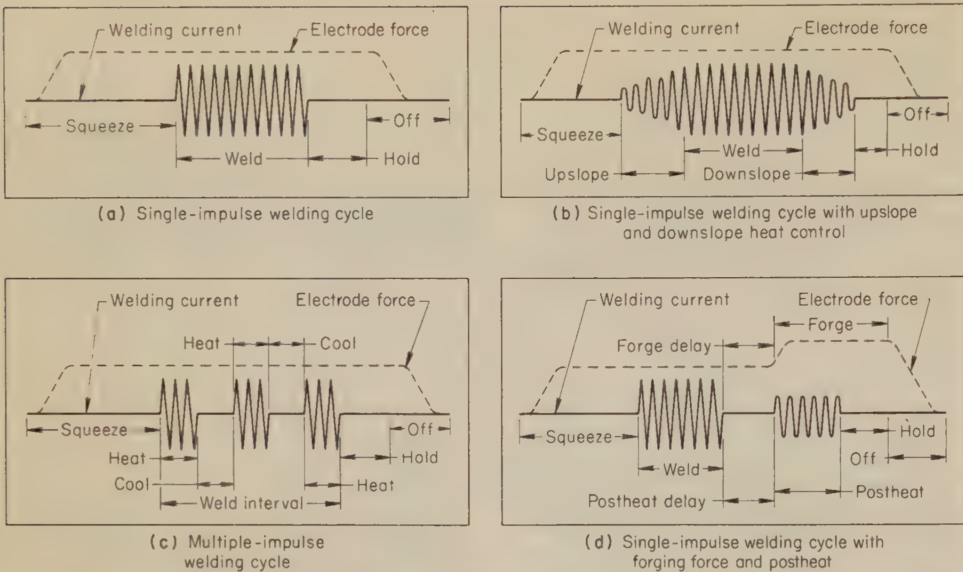
Class 2 (chromium-copper) electrodes were used in all examples in this article for which the electrode material was identified. Class 11 (copper-tungsten refractory-metal composition) insert buttons were used in Example 374 to reduce electrode wear and to permit the use of lower welding current and electrode force than are usually recommended for welding low-carbon steel.

Effect of Electrode Design. When two workpieces of similar composition and equal thickness are being welded, the tip diameters of the electrodes should be the same. However, if the workpieces are of unequal thickness, the tip diameter of the electrode contacting the thicker piece may need to be larger to maintain proper heat balance. In welding dissimilar metals, the same considerations hold true if one piece has higher electrical resistivity than the other. The dissimilarity can be compensated for by increasing the diameter of the electrode tip contacting the higher-resistance workpiece, or by using a material of higher resistance for the electrode contacting the lower-resistance workpiece.

The diameter of the weld nugget is slightly less than the diameter of the electrode-contact area. As the electrode tips are worn or increase in diameter because of "mushrooming", the diameter of the weld nugget increases. An increase in tip diameter of more than 5% can affect the weld quality, because the current density is decreased and the heat generated may be insufficient to produce a good weld.

Effect of Welding Force on Heating

Welding force, or electrode force, is the force applied to the workpieces by the electrodes during the welding cycle.



(a) Single-impulse welding cycle

(b) Single-impulse welding cycle with upslope and downslope heat control

(c) Multiple-impulse welding cycle

(d) Single-impulse welding cycle with forging force and postheat

Fig. 16. Types of resistance spot welding cycles, showing relative time for each segment, and relative values of welding current and electrode force for each segment

Electrode force, usually measured and expressed as a static value, is, in operation, a dynamic force, and is affected by the friction and inertia of the moving parts of the welding machine.

The workpieces to be spot welded must be held tightly together at the intended location of the weld to allow passage of current. However, because increasing the electrode force decreases the contact resistance of the work metal, and therefore decreases the total heat generated between the faying surfaces of the workpieces by the welding current, electrode force should not be excessive. (See the section on Effect of Surface Condition on Heating, page 415 in this article.)

The electrode force must be compatible with a welding current that is within the capacity of the equipment, and must permit the use of a welding time long enough to be reproducible. Also, the workpieces must be in reasonably intimate contact at the weld area without excessive electrode force. If the workpieces are deformed so that contact is not intimate in the weld zone, an excessively high force may be needed to overcome the deformation. Variations in weld strength and quality often result from the variations in electrode force required to bring the workpieces into proper contact, especially in the spot welding of stampings, formed workpieces, or thick sections of work metal.

Sometimes, a squeeze time longer than that normally used is needed to force the workpieces together. Also, because of the possibility of springback, hold time must be sufficiently long to permit solidification of the weld metal.

Effect of Time on Heating

The effect of time on the temperature distribution in workpieces and electrodes during spot welding is shown by the two curves in Fig. 14. The inner curve represents the temperature in each zone after 20% of the weld time has elapsed, and shows that the temperature rise at the faying workpiece surfaces (point *d*) during this period is proportionately lower than in the other zones in relation to temperature rise during the remainder of weld time.

The heat formula $H = I^2Rt$ shows that, with the total resistance held constant, the amount of heat generated in any part of the circuit is proportional to both the weld time (the time the welding current is on) and the square of the welding current. Since heat transfer is a function of time, the time required for development of the proper nugget size can be shortened only to a limited extent, regardless of how much the current is increased. Pitting and spitting (expulsion of metal), especially at the electrode contacting surfaces, results when the heat is generated too rapidly at the three contacting surfaces (zones *b*, *d* and *f* in Fig. 14).

Some reduction in weld time can be accomplished if the welding current, initial pressure and follow-up pressure are increased. Higher initial pressure is needed to prevent spitting, because of the increase in current. Higher follow-up pressure and fast follow-up are needed to maintain firm contact and adequate pressure of electrode on the workpiece until the metal of the weld has solidified.

The welding cycle is divided into four major time segments: squeeze, weld, hold and off. These are shown in Fig. 16 (see also "Time and Sequence Controls", page 403).

Squeeze time is an interval of delay between closing of the initiating switch and application of the welding current. It provides time for the solenoid-actuated head cylinder valve to operate and for the welding head to bring the upper electrode in contact with the workpiece and develop full electrode force.

Weld time is the interval during which the welding current flows through the circuit.

Hold time is the interval during which, after the welding current is off, the electrode force is held on the workpiece until the metal of the spot weld has solidified.

Off time is the interval from the end of the hold time until the beginning of the squeeze time for the next cycle. In an automatic cycle, off time is the time needed to retract the electrodes and to index, remove or reposition the work. In manual operation, it is not fixed as a maximum period by the control equipment, but depends on time taken by the operator to start a new cycle. Figure 16(a) shows the relative durations of these four basic segments for a single-impulse resistance spot welding cycle.

All of the segments are usually expressed in cycles, meaning the number of cycles in a 60-cycle system, where one cycle is $\frac{1}{60}$ sec.

The simplest welding cycle supplies uniform welding current and electrode force throughout the weld interval, but the addition of slope control enables the welding current to be varied. As shown in Fig. 16(b), a welding cycle that incorporates slope control has an increase in current before the weld and a decrease after the weld.

Upslope permits the welding current to be increased over several cycles from a low value to that needed for welding, instead of having the full welding current applied instantly. A

Table 4. Recommended Practices for Single-Impulse Resistance Spot Welding of 1010 Steel With Class 2 Electrodes (a)

Thickness of thinnest outside piece (*t*), in.(b)	Electrode dimensions: Body diameter, in.	Electrode dimensions: Face diameter, in.(c)	Net electrode force, lb	Weld time, cycles (60 cps)	Welding current (approx), amp	Minimum contacting overlap, in.	Minimum weld spacing, in.(d)	Nugget diameter (approx), in.	Minimum breaking load in shear, lb, for work metal with tensile strength of: Less than 70,000 psi	70,000 psi or more
0.010	3/8	1/8	200	4	4,000	3/8	1/4	0.10	130	180
0.021	3/8	3/16	300	6	6,500	7/16	3/8	0.13	320	440
0.031	3/8	3/16	400	8	8,000	7/16	1/2	0.16	570	800
0.040	1/2	1/4	500	10	9,500	1/2	3/4	0.19	920	1200
0.050	1/2	1/4	650	12	10,500	9/16	7/8	0.22	1350	...
0.062	1/2	1/4	800	14	12,000	5/8	1	0.25	1850	...
0.078	5/8	5/16	1100	17	14,000	11/16	1 1/4	0.29	2700	...
0.094	5/8	5/16	1300	20	15,500	3/4	1 1/2	0.31	3450	...
0.109	5/8	3/8	1600	23	17,500	13/16	1 5/8	0.32	4150	...
0.125	7/8	3/8	1800	26	19,000	7/8	1 3/4	0.33	5000	...

SOURCE: "Recommended Practices for Resistance Welding", AWS C1.1; also, "Welding Handbook", 6th Ed., Section 2, American Welding Society, 1969. Published here by permission.

(a) Steel should be free from scale, oxides, paint, grease and oil. (b) Thickness of thinnest outside piece (*t*) determines welding conditions. Data are for total thickness of pile-up not exceeding 4*t*; maximum ratio between two thicknesses, 3 to 1. (c) For type A, D and E faces. Body diameters apply also to type F electrodes with 3-in. spherical-radius face. (d) Center-to-center spacing for two pieces for which no special precautions need be taken to compensate for shunted-current effect of adjacent welds; for three pieces, increase spacings here by 30%.

Table 5. Recommended Practices for Single-Impulse Resistance Spot Welding and Postheating of Medium-Carbon and Low-Alloy Steels With Class 2 Electrodes(a)

Steel to be welded: Type and condition(b)	Steel to be welded: Thickness (t) of each piece, in.(c)	Dimensions of upper and lower electrodes: Body diameter, in.	Face diameter, in.	Face radius, in.	Net electrode force (weld and temper), lb	Time, cycles (60 cps): Weld	Quench	Temper	Welding current (approx), amp	Tempering current, % of welding current	Minimum contacting overlap, in.	Minimum weld spacing, in.(d)	Nugget diameter (approx), in.	Minimum breaking load of weld, lb: In shear	In tension	Ratio, tensile to shear breaking load, %
1020, HR	0.040	⅝	¼	6	1475	6	17	6	16,000	90	½	1	0.23	1,360	920	68
1035, HR	0.040	⅝	¼	6	1475	6	20	6	14,200	91	½	1	0.22	1,560	520	33
1045, HR	0.040	⅝	¼	6	1475	6	24	6	13,800	88	½	1	0.21	2,000	680	34
4130, HR	0.040	⅝	¼	6	1475	6	18	6	13,000	90	½	1	0.22	2,120	640	30
4340, N&T	0.031	⅝	3/16	6	900	4	12	4	8,250	84	7/16	¾	0.16	1,084	290	27
	0.062	¾	5/16	6	2000	10	45	10	13,900	77	⅝	1½	0.27	3,840	1440	37
	0.125	1	⅝	10	5500	45	240	90	21,800	88	⅞	2½	0.55	13,680	4000	29
8630, N&T	0.031	½	3/16	6	800	4	12	4	8,650	88	7/16	¾	0.16	1,220	524	43
	0.062	⅝	5/16	6	1800	10	36	10	12,800	83	⅝	1½	0.27	4,240	2200	52
	0.125	1	⅝	10	4500	45	210	90	21,800	84	⅞	2½	0.55	13,200	4500	34
8715, N&T	0.018	½	⅛	6	350	3	4	3	3,900	85	7/16	⅝	0.10	400	200	50
	0.062	⅝	5/16	6	1600	10	28	10	12,250	85	⅝	1½	0.27	3,300	1800	55
	0.125	1	⅝	10	4500	45	180	90	22,700	85	⅞	2½	0.55	12,760	4500	35

(a) Steel to be welded should be pickled, or otherwise cleaned, to obtain a surface contact resistance not exceeding 200 microhms. (b) HR = hot rolled; N&T = normalized and tempered. (c) Welding conditions are for joining two pieces of equal thickness, each of thickness t. (d) Minimum spacing for which no special precautions are needed to compensate for shunted-current effect of adjacent welds. [SOURCE OF TABLE: Same as Table 4]

low initial welding current reduces or prevents expulsion of metal (spitting) when the current is first applied. Upslope control is used for welding at high current values, and for welding scaly stock as well as most kinds of plated metals.

Downslope permits the welding current to decay gradually to a low value instead of ending suddenly, and it helps to produce good welds in some types of heat treatable metals by lengthening the cooling-time gradient. It is rarely needed in welding low-carbon steel, particularly if the carbon content does not exceed 0.15%, but is used when cooling rate must be limited, as in welding hardenable steels.

The high welding currents and long weld times needed for welding sheets greater than ⅛ in. in thickness may cause overheating of the electrodes. This can be minimized by applying the current in pulses during the weld interval, as shown in Fig. 16(c). Heat is dissipated more rapidly from the electrodes than from the workpieces. Therefore, during the cool time, when the welding current is off, the electrodes dissipate most of their heat while the workpieces lose very little. With a series of impulses each followed by a cooling period, the workpieces are brought to welding temperature while the electrode temperature remains at a safe level. A multiple-impulse weld interval was used in Example 373 (see page 408) in spot welding of an automotive-wheel assembly.

Two other elements that can be added to a welding cycle are forge and postheat, both shown in Fig. 16(d). They are both used chiefly for grain refinement on hardenable carbon and alloy steels, and are not used on low-carbon steel. After welding there is a short delay, or current-off period, to allow the weld to cool before the application of a tempering current. Postheat, during which the current is on at a low value, is followed by a hold time. During postheating, the electrode force may be increased, as shown in Fig. 16(d). This increased force is called a forging force and is applied during the postheat and hold times. The welding force usually is maintained until the postheat current is applied, after which it is increased to the forging force.

Effect of Workpiece Surface Condition on Heating

For consistent production of spot welds of the highest quality, the resistance at the workpiece surfaces that contact the electrodes (zones b and f in Fig. 14) must be kept to a minimum. This can be done by having smooth, clean work-metal surfaces and by controlling the electrode force. If the workpiece surfaces that contact the electrodes have too high a contact resistance, the temperature rise at these surfaces is almost as fast as at the faying surfaces (zone d in Fig. 14). Also, inconsistent results can be obtained because of variations in the contact resistance and corresponding variations in the time it takes for current flow to be established.

The surfaces of metal sheets are not smooth on a micro scale, and the actual metal-to-metal contact area may be only a small prcentage of the entire contact surface when light electrode pressures are used. As the electrode force is increased, the high spots are depressed, increasing the actual metal-to-metal contact area and thus decreasing the electrical resistance. Increased electrode force also decreases the resistance at the interface of the workpieces. When the electrode material is softer than the work metal, the application of a given electrode force will result in better contact at the contacting surfaces between electrodes and workpieces than at the interface of the two workpieces.

Although electrode force does not enter directly into the heat formula $H = I^2Rt$, its effect on electrical resistance has a direct effect on the flow of the welding current. Surface resistance is inversely proportional to electrode force.

Surface Preparation. Recommended practices for spot welding steel, as given in Tables 4, 5 and 6, call for the work metal to be free from scale, oxides, paint, grease and oil.

The work to be welded, or, as a minimum, the faying surfaces, should be cleaned to ensure that the welds will be free of inclusions. Dirt, scale, rust and oxide film that may come in contact with the electrodes should be removed or reduced to ensure good surface appearance of the welds. Also, removal of foreign substances from workpiece surfaces reduces electrode pickup and consequently increases electrode life.

A film of dirt or oil can be removed from the surfaces of the workpieces by vapor degreasers and chemical baths; however, careful hand wiping of the surfaces to be spot welded may be sufficient. Oxide films can be removed by mechanical methods; the action must be severe enough to cut through the film, but must not be so severe as to cause the formation of a rough or scratched surface.

Where it is impractical to use pickled or cold rolled steel, the surfaces to be welded can be machined, ground or wire brushed far enough back from the edge of the workpiece to clear the electrodes, or for a distance equal to the overlap. Annealing in a reducing at-

Table 6. Recommended Practices for Multiple-Impulse Resistance Spot Welding of 1010 Steel With Class 2 Electrodes(a)

Thicknesses (t-1 and t-2) of steel to be joined, in.: t-1	t-2	Electrode dimensions: Body diameter, in.	Face diameter, in.(b)	Net electrode force, lb	Weld time, impulses(c): Single welds	Adjacent welds with center-to-center spacing of: 1-2 in.	2-4 in.	Welding current (approx), amp	Minimum contacting overlap, in.	Minimum nugget diameter, in.	Minimum breaking load in shear, lb(d)
⅛	⅛	1	7/16	1800	3	5	4	18,000	⅞	⅜	5,000
⅛	3/16	1	7/16	1800	3	5	4	18,000	⅞	⅜	5,000
⅛	¼	1	7/16	1800	3	5	4	18,000	⅞	⅜	5,000
3/16	3/16	1¼	½	1950	6	20	14	19,500	1⅛	9/16	10,000
3/16	¼	1¼	½	1950	6	20	14	19,500	1⅛	9/16	10,000
3/16	5/16	1¼	½	1950	6	20	14	19,500	1⅛	9/16	10,000
¼	¼	1¼	9/16	2150	12	24	18	21,500	1⅜	¾	15,000
¼	5/16	1¼	9/16	2150	12	24	18	21,500	1⅜	¾	15,000
5/16	5/16	1½	⅝	2400	15	30	23	24,000	1½	⅞	20,000

(a) Steel should be free from scale, oxides, paint, grease and oil. (b) For type A, D and E faces. Body diameters apply also to type F electrodes with 3-in. spherical-radius face. (c) Each impulse consists of 20 cycles on (heating) and 5 cycles off (cooling), at 60 cycles per second. (d) For steel with a tensile strength of less than 70,000 psi. [SOURCE OF TABLE: Same as Table 4]

mosphere is also an acceptable cleaning method for some metals.

Abrasive blast cleaning methods using sand, coarse grit or shot usually are not satisfactory because particles of sand or scale are left embedded in the surface. Fine, sharp steel grit is satisfactory in some applications.

For information on metal cleaning, see Volume 2 of this Handbook.

Effect of Oil Coatings. Thin coatings of oil on cold rolled or hot rolled pickled and oiled steel have little effect on the quality of spot welds. Tests have shown that the strength of spot welds made on steel having a thin coating of oil is ordinarily about 2 to 3% less than that of spot welds made on the same metal after removing the oil by degreasing.

Excessive amounts of oil should be wiped off or removed in a degreasing operation. The oil itself may not be detrimental to the weld, but the dirt and other contaminants adhering to the oil may cause poor welds.

Effect of Rust, Scale or Oxide. Steel coated with rust, scale or thermally produced black or blue oxide finishes can be resistance spot welded in production, but quality and consistency of welds are lower than on steel from which these coatings have been removed. Thin films that have low and uniform electrical resistance have the smallest effect on welding. Steel that is coated with extremely thick and nonuniform mill scale may not be weldable on a practical production basis without first removing the scale.

Steel on which uniform but heavy mill scale or oxide coatings are present can be welded in production by applying low-to-medium current in a series of pulsations at fairly high electrode pressure. The electrical conductivity of mill scale or oxide increases with temperature, and these coatings become fairly good conductors when red hot. Because of the variable time needed to break through the coating and establish current flow, manual timing gives more satisfactory results than automatic timing.

When metal having heavy scale or oxide coatings is welded, much or all of the scale or coating on the faying surfaces remains in the welds, regardless of current, surface resistance, or electrode pressure. These inclusions in the weld metal can cause voids, blowholes and other internal defects that may sometimes be difficult to detect.

Effect of Weld Spacing on Heating

Shunting occurs when a second spot weld is made so close to the first one that the welding current can flow either through the metal at the first weld or through the metal between the electrodes at the point of the second weld. The welding current will flow in inverse proportion to the resistance of the two paths. Division of current will depend chiefly on the ratio of resistance of the base metal to interface resistance at the point of the second weld.

When making a second and following spot welds, the metal between the electrodes becomes a divided circuit; part of the current travels through the metal to the previously made spot weld, while the remainder travels through the metal between the electrode faces at the point of the second weld. If the distance to the first spot weld is great enough, the resistance of the path through the first spot weld, compared to that directly through the metal, will be high, and the shunting effect can be neglected. If the distance to the first spot weld is short, a significant fraction of the current will be shunted through the first spot weld.

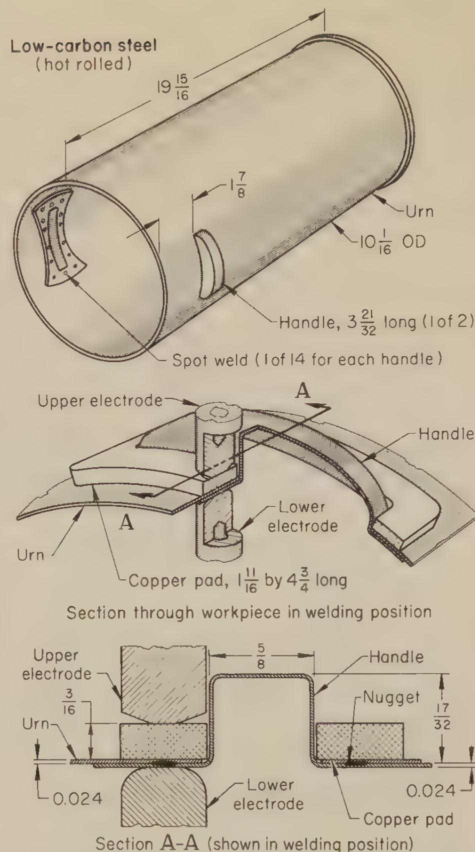


Fig. 17. Sand urn on which electrode indentations on exterior surface were avoided by using a copper pad to diffuse force of upper electrode in spot welding of handles **(Example 375)**

As the temperature of the metal between the electrode tips rises, the resistance at that point increases, thus adding to the shunting effect. Metals having high electrical resistivity are less influenced by the shunting effect than are low-resistivity metals.

The minimum spacing of spot welds in low-carbon steel workpieces depends on stock thickness, diameter of the fused zone, and cleanness of the faying surfaces. The minimum recommended weld spacing for low-carbon, medium-carbon and low-alloy steels is given in Tables 4, 5 and 6. Welds can be made at less than recommended minimum spacing without significant shunting by using higher current and electrode force, shorter weld time and fast follow-up.

If spot welds are made too close to the edge of a sheet or flange, there is an insufficient volume of base metal to withstand electrode pressure and heating. This results in a reduction in the effective force along the edge and uneven heating, causing the hot metal to be expelled from the weld. When spot welds are made too close to an upright flange or sidewall, arcing may occur between the electrode and workpiece, or there may be a poor fit at the faying surface because of the bend radius. If large-diameter electrodes are needed because of the metal thickness, eccentric (offset) faces may be used.

The minimum contacting overlap between two pieces of metal depends somewhat on the metal thickness, which in turn governs the electrode diameter and diameter of the fused zone. The minimum overlaps for low-carbon, medium-carbon and low-alloy steels are given in Tables 4, 5 and 6.

Effect of Surface-Finish Requirements on Heating

In spot welding of assemblies that are to be porcelain enameled or painted, or are to receive other decorative surface finishes, the surface condition and close fit of parts after welding are as important as weld strength. Excessive indentation, overheating of the outside surfaces, spatter and crevices interfere with the finishing operations, and must be avoided.

Welding schedules and conditions must be selected that will produce a weld of adequate strength with a minimum of indentation and minimum evidence of heating. This requires a uniform welding procedure that is best obtained with automatic control of current, time and force. Electrode faces should be dressed at regular intervals, before they have worn so much that unsatisfactory spot welds are produced. The workpieces should be cleaned thoroughly before welding.

In the following example, electrode indentations that were noticeable after spray painting were avoided by using a pressure pad between the electrode and the outer surface of the work.

Example 375. Use of a Conductive Pressure Pad Between an Electrode and the Work To Avoid Electrode Indentation (Fig. 17)

When flanged press-drawn handles were inserted through slots in a sand urn and joined to the inside wall of the urn with 14 spot welds along the flange of each handle (Fig. 17, top view), small dents were present on the outside of the urn, at locations of contact by the face of the upper electrode. These dents were noticeable after spray painting and caused a rejection rate of 5 to 6%, which was considered to be unacceptable.

The dents were avoided by placing a conforming copper plate, or pressure pad, between the upper (outside) electrode and the urn wall, as shown in the middle and bottom views in Fig. 17. This pressure pad fit over the handle and made general contact with the steel urn wall to provide an electrical circuit. The force of the upper electrode, although not reduced, was spread out by the pad so that, after the urn was painted, no dents were visible at the weld spots.

The stress field from the lower (inside) electrode, which was critical for satisfactory spot welding, was not greatly modified by this change, nor was the flow of current through the joint changed substantially.

The welding machine was a foot-operated rocker-arm type, supplied with single-phase alternating current; rating at 50% duty cycle was 20 kva. The upper elec-

trode had a type A (pointed) face, and the lower electrode a type B (dome) face; both were of class 2 material. The No. 2 transformer tap setting was used for welding.

Welding Schedules

Low-carbon steel can be satisfactorily resistance spot welded using wide ranges of time, current and electrode force. Limitations in machine capabilities in any of these variables can be partly compensated for by making suitable adjustments of the others. Practices recommended by the American Welding Society for resistance spot welding of low-carbon, medium-carbon and low-alloy steels are listed in Tables 4, 5 and 6.

The data in these tables can serve as starting points for the establishment of optimum settings for welding of workpieces on which previous experience is lacking, and as an approximate guide to the results that may be expected when good shop practice is followed in resistance spot welding. They are subject to adjustment as necessary to meet the requirements of individual applications.

In addition to giving recommended welding schedules and expected weld properties, these tables also provide guidance on the permissible ratios of thickness for the workpieces, limits on total thickness of pile-up, and recommendations on minimum contacting overlap and minimum weld spacing.

Setting-up Welding Schedules. A typical sequence of steps for determining the most satisfactory conditions for resistance spot welding work for which previous experience is lacking is given in the following list. The usual criteria for satisfactory welds in steps 1 to 4 are penetration, nugget diameter and indentation suitable for the application, and the absence of porosity and gross defects.

1. **Make a preliminary selection of electrode force** for the work to be welded and the electrodes to be used. Tables of recommended practices such as Tables 4 to 7 may provide starting points for this selection, as well as guidance in choosing preliminary values of current, weld time and hold time for making trial welds to verify or correct this preliminary selection of electrode force.
2. **Establish the weld time and hold time.** This is done by evaluating trial welds made at several levels of current for each of a number of combinations of weld time and hold time. Squeeze time is not critical in welding trials and is usually set at a convenient value that is long enough to allow for a wide range of test conditions.
3. **Select electrode force.** Using the established combination of weld time and hold time, make welds at several different current levels, using a number of values of electrode force to cover a wide range of force.
4. **Select the welding current.** Using the established weld time, hold time and electrode force, make test welds at current levels that cover a wide range of amperage.
5. **Verify selection of conditions.** Make trial runs under the welding conditions established by steps 1 to 4, to verify these selections as well as to establish reference data on weld quality and reliability for use in process control. A more complete evaluation than for steps 1 to 4 is performed at this stage (see the discussion in the section on Quality Control, which follows in the next column).

If the results of trial runs in step 5 are not satisfactory, the five-step procedure may be repeated, with changes in the welding variables being made as indicated by the test results. Changes in equipment, electrode material and electrode design may also be made at this time, and the five-step procedure (or a shortened version) repeated until acceptable results are obtained.

The five steps described above not only determine optimum values for each of the welding variables, but also establish ranges of satisfactory values for them and the criticality or noncriticality of each.

The sequence of steps followed in setting up a resistance spot welding schedule may vary, depending on special aspects of the equipment or the work, the extent of experience with similar types of work, and requirements imposed by the purchaser or applicable specifications.

When adjustment of welding conditions is needed at the start of or during production runs, the adjustment is usually made on weld time, hold time or current, whichever is most convenient and effective. Work-metal variables that necessitate adjustments in welding conditions, and a system used by one manufacturer to control these variables and provide for the continuing setting of schedules on the basis of pre-acceptance evaluation of raw material, are described in Example 377.

Quality Control

General practice in resistance spot welding is to base quality control on weld properties and also on the uniformity and consistency of results. For any given requirement, a minimum value may be set that must be equaled or exceeded by all test results; it is often also required that all tests in a given sample should fall within ±10% of the mean for that sample.

The quality of spot welds generally is checked by visual inspection and by destructive testing. Nondestructive testing methods are not ordinarily used in inspection of resistance spot welds.

For a detailed discussion of standard test methods and quality-control procedures for resistance welding, see AWS C1.1, "Recommended Practices for Resistance Welding", Section V.

Quality standards must be related to the requirements of the specific application. It is seldom possible, for instance, to obtain maximum joint strength and minimum indentation using the same machine settings, as shown in Fig. 15.

Visual Inspection. On the surface of a resistance spot welded assembly, the weld spot should be uniform in shape and relatively smooth, and it should be free of surface fusion, deep electrode indentations, electrode deposits, pits, cracks, sheet separation, abnormal discoloration around the weld, or other conditions indicating improper maintenance of electrodes or functioning of equipment. However, surface appearance is not always a good indicator of spot weld quality, because shunting and other causes of insufficient heating or inadequate penetration usually leave no visible effects on the workpiece.

Destructive testing can be performed on the actual workpiece or on test specimens. For small, inexpensive parts, actual production samples from each machine are taken on a random-selection basis or at prescribed regular intervals for destructive testing. Test coupons are not entirely satisfactory, because of the effect of a different amount of magnetic material in the throat of the welding machine on welding current. They are used, however, where production parts are large or costly, and with experience in interpretation of results can give valuable information on the quality of production welds.

Destructive tests made on spot welds include tension-shear, tension, peel, impact, twist, hardness and macro-etch tests. Fatigue tests and radiography have also been used.

Strength of the weld is usually determined by the tension-shear and tension tests. Separation of the joint as observed in one of the first five tests can be used to approximate the diameter of the weld nugget. Examination of macro-etch specimens can reveal the nugget diameter and penetration, and the structure of the weld.

Quality standards on nugget diameter and penetration vary with the requirements of the specific application. For maximum weld strength, a rule of thumb that can be applied as a starting point in welding most metals, in the absence of more specific requirements, is that the minimum nugget diameter should be 0.06 in. plus three times the thickness of the thinnest workpiece. Tables 4, 5 and 6, as developed by the American Welding Society, give recommended nugget diameters for spot welding low-carbon, medium-carbon and low-alloy steels, in relation to shear strength of the welds. These nugget diameters are for welds of the highest average shear strength that can ordinarily be obtained in production with high reliability.

Penetration, or the depth that fusion extends into the outer workpieces, should be 20 to 80% of the workpiece thickness, with welds of maximum strength usually being obtained when penetration is about 70% of stock thickness. When workpieces of unequal thickness are welded, penetration into the thicker piece ordinarily need not exceed the penetration into the thinner piece.

Where surface finish is critical, extent of indentation, discoloration, spatter and sheet separation may be as important as weld strength.

The structure of a spot weld in low-carbon steel ordinarily has the following features:

1. A columnar dendritic structure in the fusion zone
2. A heat-affected outer zone showing gradual transition from a coarse overheated structure through a normalized region, to the original structure of the unaffected base metal
3. A narrow ferritic zone in the interface of the overheated and unaffected zones. This zone is not always well defined, particularly at the interface of the two workpieces.

Process Variables That Affect Weld Quality. In addition to current, electrode force, and timing, the process

variables that affect weld quality in resistance spot welding include:

1 Ability of the welding equipment to operate consistently at the specified current in continuous production
2 Closeness of fit of the components to be welded
3 Strength and rigidity of fixtures
4 Adequacy of clamping.

When only one or a few spot welds are used to join workpieces, the probability of exceeding the duty-cycle rating of the machine is much less than when many spots are made in rapid succession. Exceeding the duty-cycle rating causes the transformer to overheat, resulting in underheating of the workpieces and production of poor-quality welds (or, if extreme or of sufficiently long duration, in shutting down the equipment).

Poorly fitting workpieces may not permit proper contact. Poor contact can cause insufficient flow of current, small-diameter welds, or welds that have inadequate fusion and pull apart because of springback.

Magnetic materials in or near the throat of the machine affect kva demand and power factor, and should not be used in fixtures that are to be placed in the throat of the machine. The fixtures should have sufficient strength and rigidity to prevent warping of workpieces.

In spot welding long sections of thick material, the four process variables listed above have a critical effect on weld quality. In the example that follows, many welding trials and substantial changes in equipment and procedures were needed to solve problems of weld quality related to these variables.

Example 376. Changes in Major Process Variables To Avoid Warping of Workpieces and Overheating of Equipment in Making 73 Spot Welds in a Long Assembly of Thick Steel (Fig. 18)

A total of 73 spot welds were made in joining two steel workpieces, each 75 in. long and 0.089 in. thick (0.178-in. total thickness), as shown in Fig. 18. Fit-up in the overlapping portions of the workpieces, where the welds were to be made, was very poor in spots. In the first welding trials, a heavy-duty portable welding gun was used with a fixture equipped with hand-operated clamps.

Two major problems were encountered: (*a*) as the welds were made, the clamps loosened so that the assembly was twisted and bent when removed from the fixture; and (*b*) weld strength and nugget diameter deteriorated progressively after 38 or 39 welds, and the last few welds failed even to hold the workpieces together.

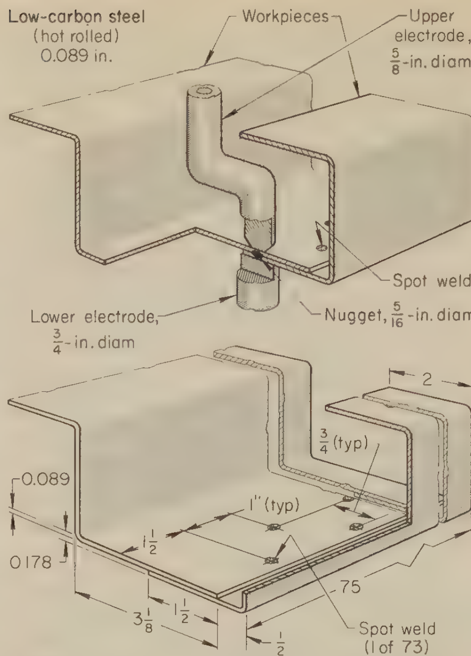
In an attempt to eliminate the warping of the assembly and loosening of the clamps during welding, several welding trials were conducted in which the welds were made in various staggered sequences. None of these efforts substantially reduced the amount of warping or the loosening of the clamps.

Further experimentation led to the adoption of the following three changes to improve fit-up and eliminate warping of the workpieces and loosening of the clamps during welding: (*a*) the forming dies were reworked to improve fit-up; (*b*) the welding fixture was rebuilt to make it more rigid; and (*c*) the hand clamps were replaced by stronger air-operated clamps, and more clamps were used.

The addition of a second welding gun and control of cooling-water flow rates in the equipment were used to eliminate the progressive deterioration of weld characteristics in making the 73 spot welds.

It appeared that the inability to produce 73 sound welds in succession was the result of cumulative temperature rise in the welding equipment. When two welding guns, each connected to a separate transformer, were used alternately and with adequate cooling-water flow, acceptable weld quality was obtained in continuous production. Apparently, the "off" time for each welding unit allowed sufficient cooling of the welding guns and power-supply components. To maintain adequate cooling of the welding components, the flow of cooling water in the system was controlled with the aid of flowmeters at the rates shown in the table that accompanies Fig. 18.

Additional equipment details and welding conditions are also given in the table that accompanies Fig. 18.



Equipment Details

Welding guns (2)	Portable, heavy-duty, air operated
Transformers (2)	Series-parallel with 5-step tap switch(a)
Rating at 50% duty cycle	200 kva (each transformer)
Upper electrode	Offset body, ⅝-in. diam, with ⅜-in.-diam type E (truncated) face(b)
Lower electrode	Type C (flat), ¾-in. diam
Cables (2)	450 MCM (450,000 circular mils), kickless, water cooled, 6 ft long
Disconnect switches	800 amp

Welding Conditions

Transformer tap setting	Series and No. 3 tap
Electrode force	1400 lb
Squeeze time	40 cycles
Hold time	25 cycles
Weld time	2 pulses of 12 cycles weld, 6 cycles cool
Cooling-water flow rate:	
In cables and electrodes	1½ gal per min
In transformers	1¾ gal per min

(a) Phase-shift heat control was not used. (b) Space was not sufficient for a ¾-in.-diam electrode.

Two water-cooled transformer-and-gun units were used alternately to avoid overheating; and rigid fixturing, air-operated clamps, and crowned workpieces were used to avoid warping.

Fig. 18. Long, poorly fitting assembly of thick steel for which overheating and warping were avoided in spot welding (Example 376)

Workpiece variables that affect weld quality include work-metal composition, heat treatment, and degree of cold work before welding. Consistency of hardness, strength, stock thickness, phase distribution and alloy content is needed to ensure consistency of results in resistance welding of any material. Variations in work-metal properties that have the greatest effects on weld quality usually can be detected by relatively simple tests such as measurement of tensile strength or hardness tests on the raw material.

In the example that follows, variations in hardness and tensile strength of greater than ±10% from an established mean value, or in stock thickness, were found to have adverse effects on quality of spot welds, and methods were developed to control these variables. (Related programs, which made use of the same control of raw material and the same system for evaluating welding machines and welds, were applied to gas tungsten-arc and gas metal-arc spot welding.)

Example 377. Procedure for Control of Work-Metal and Processing Variables To Ensure Quality of Spot Welds (Fig. 19)

In one plant, failures of spot welds in sheet-metal assemblies were threatening to halt production. The exact contribution of each factor involved could not be assessed accurately, but excessive variation in quality of raw material was suspected as one of the chief contributors. Most of the assemblies welded were made of commercial quality, cold rolled low-carbon (0.13 max C) steel sheets 0.060 or 0.048 in. thick. Class 2 electrodes were used for all spot welding of low-carbon steel.

A five-part program instituted to bring the quality of the spot welds under control included:

1 Establishment of standards for incoming raw material
2 Initiation of a quality-control program for incoming stock, based on the standards established in step 1
3 Determination and systematic recording of machine capabilities for making the spot welds
4 Initiation of a program of electrode maintenance
5 Establishment of standards for in-process inspection and control.

The entire program was put into effect after completion of a three-year study and development period.

Standards for Incoming Material. A three-year study was made of all incoming steel sheet from all sources to determine which characteristics of the material most affected weld quality. At the end of this study, the findings were incorporated into a plant purchasing specification for sheet steel.

Variations in thickness, tensile strength and hardness were found to have the largest effects on weld quality, and plant standards were set up for these and other characteristics. Sheet thickness was required to conform to AISI standards as described in the Steel Products Manual for Carbon Steel Sheets. Tensile strength had to be within 10% of an established mean, and hardness had to be less than Rockwell B 60.

Sheet steel had to be free from laminations and to be capable of being bent flat on itself in any direction at room temperature without cracking along the bend. It also had to pass weldability tests for resistance spot welding, as outlined below under "Quality Control of Incoming Stock", for acceptance under the plant purchasing specification for sheet steel.

Quality Control of Incoming Stock. All incoming stock was subjected to routine identification and visual examination, and to inspection procedures established by the special purchasing specifications written under the first step of this quality-control program.

Two sheets of steel were selected at random from each incoming shipment and from them were sheared a number of 1-by-6-in. coupons for testing. (Coupons were cut from more than two sheets if quality of heat was in doubt.) Ten of these coupons were tested for tensile strength (breaking load), others were tested for hardness, and the thickness of the steel was measured.

Finally, ten coupons were spot welded to make five samples. Of these samples, four were broken in tensile-shear tests, and one was sectioned and examined for penetration and diameter of weld nugget. Penetration of the nugget was to be a minimum of 50% of sheet thickness into each member of any joint, and variation of tensile-shear strength from standard was to be no more than ±10%.

Material that passed these tests was accepted and released for production. Figure 19 shows the amount of variation in tensile strength (breaking load), hardness and thickness of incoming stock, and in tensile-shear strength of spot welded joints between samples, over a ten-year period, for the two thicknesses (0.048 and 0.060 in.) that comprised most of the steel sheet that was resistance spot welded.

Machine Capability. Sample coupons from shipments of steel sheet that had been tested and found to conform to the plant purchasing specification were used in evaluating the capability of each production resistance spot welding machine.

In the initial qualification of a machine, the settings on the machine were varied systematically and welds were made and checked to establish control settings for the machine on the thicknesses of stock to be run on that machine. Records of these control settings were kept for use in setting up for production runs.

Before making a production run in any machine, the control settings on that machine were tested by welding four pairs of specimens for inspection. Three of these samples were pulled apart in tensile-shear tests, and the fourth was sectioned for metallographic examination. The production welding machine was adjusted until the welds met the quality-control standards.

Then 25 test welds were made to determine the uniformity of operation of the machine. Of these 25, five were sectioned and 20 were tested to destruction in tensile-shear tests.

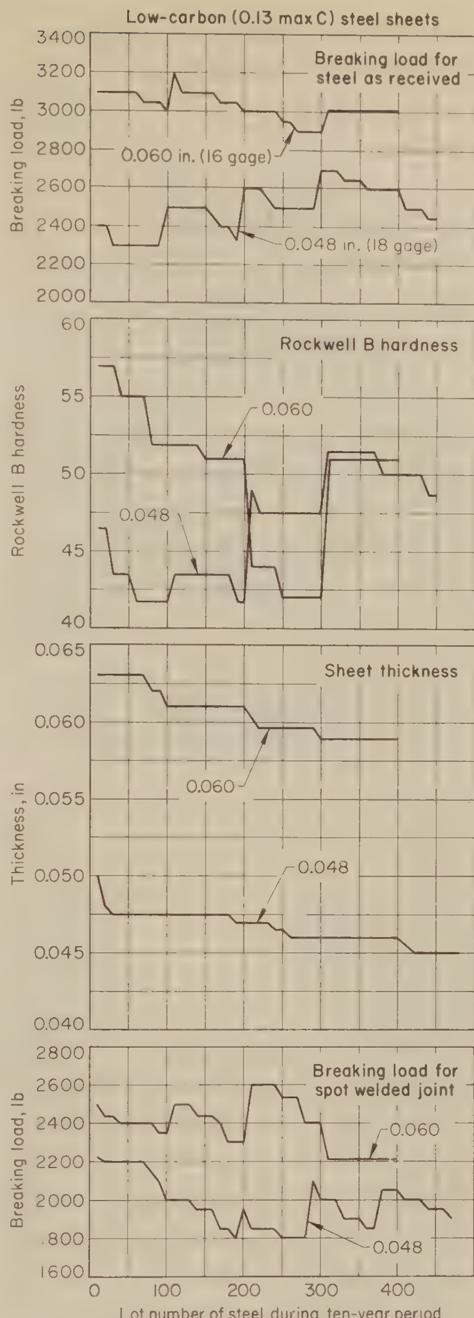
If the test samples were acceptable, the machine settings were approved for production. Before each start-up, four samples were made and tested to ensure that meanwhile none of the settings had changed.

Electrode Maintenance. Shape of the electrode face was found to have an important influence on weld quality. Usually, the best spot welds were made by electrodes with radius faces (type F, Fig. 9). The spherical radii of the electrode faces ranged from 2 to 6 in. For even penetration of stock with equal thickness in both members, a 2-in. radius was normally used on both electrode faces.

Sometimes, an electrode with a flat face (type C, Fig. 9) was used with an opposing electrode having a radius face. When sheets of different thicknesses were joined, electrode faces with differing radii were used; this ensured heat balance and resulted in equal penetration of both members of the joint.

The face contour of radius-face electrodes was maintained by dressing with a specially shaped paddle, faced with 240-mesh aluminum oxide cloth. The faces of the paddle had a concave surface that fit the spherical end of the electrode to be dressed. After eight hours of use, the electrodes were replaced, and the worn ends were remachined to the original spherical shape, regardless of their condition, as a preventive-maintenance practice.

In-Process Inspection. For in-process inspection, random spot welded assemblies were taken from the production line and sectioned for metallographic examination,



Equipment Details(a)

Welding machine ......220-v, 60-cycle, 3-phase press type; throat, 10 by 36 in.
Rating at 50% duty cycle ....100 kva
Secondary voltage, max ....4.9 v
Secondary current, max ....70,000 amp
Electrode force ....3000 lb max(b)
Electrode ....Type F, 2-in. radius; class 2

Typical Welding Conditions(a)	0.048-in. sheet	0.060-in. sheet
Heat-control setting, %	36	36
Electrode force, lb	750	750
Squeeze time, cycles	40	40
Weld time, cycles	10	12
Hold time, cycles	40	40
Heat time, cycles(c)	6	9
Cool time, cycles(c)	4	4

(a) Over the ten years, various welding machines were used; details here illustrate general machine capability. Operating conditions varied among machines. (b) At 80-psi air pressure. (c) Not available on all machines.

Data plotted represent mean values as determined for each ten lots of steel received.

Fig. 19. Ten-year record of characteristics of sheet and spot welded joints, used to establish process controls (Example 377)

or tested to destruction in a tensile-shear test. As in the weldability tests done for quality control of incoming stock, nugget penetration had to be a minimum of 50% of sheet thickness into each member of the joint, and tensile-shear strength could not vary more than ±10% from the established standard. The frequency of testing depended on the cost of the assembly, and on the need for control as indicated by previous history of variation. These in-process inspection tests were in addition to the routine tests done just before each production run, as described above under "Machine Capability".

Results of Program. Since several phases of this program were developed simultaneously, and since their development was interdependent, several minor adjustments had to be made in the level of the standards in the first year or two of operation. A record of the first 17 years under this program showed that the problem of failure of spot welds in finished assemblies was completely eliminated, and that there were no reports of failure of weldments in the field.

Overlapping Spot Welds

Spot welds that overlap instead of being spaced apart frequently are used to produce leakproof seams. Normally, these seams are made by resistance seam welding; however, when the seam or the workpieces are too small for conventional electrode wheels to track, or when a workpiece interferes with the operation of a cup-type seam welding electrode, individual spots must be made with modified resistance spot welding methods.

In the following example, when overlapping spot welds were used instead of spot welding plus silver brazing to make an airtight seam, production rate was increased and cost was reduced.

Example 378. Use of Overlapping Spot Welds To Increase Production Rate and Reduce Unit Cost in Making an Airtight Seam (Fig. 20)

The type 430 stainless steel outer wrap of a gasoline-burning car heater was joined to the nickel-plated low-carbon steel exhaust tube of the heater as shown in Fig. 20. The joint had to be strong and, for safety, airtight when tested at a pressure of 5 psi. Originally, the assembly was joined by separate spot welds, for strength, and then the joint was silver brazed, to make it airtight. Acceptable parts with strong, airtight joints were made by this method, but a faster and less costly method for joining was needed to meet increased demand.

Seam welding was considered, but the 1¾-in.-diam circular seam was too small to track with wheel electrodes. Therefore, a method of making overlapping spots in a press-type resistance spot welding machine was adopted.

The head of the welding machine was equipped with an automatic rotary-indexing mechanism to which was mounted a holder for two upper electrodes 180° apart, which were operated against a one-piece lower electrode that conformed with the internal contour of the components at the joint (see Fig. 20). Clamps held the components on the lower electrode holder during welding. The upper electrodes were ⅝ in. in diameter, with tips machined to 5/32 in. in diameter, and had a 45° offset. All electrodes were made of RWMA class 2 material. The upper electrodes were connected to the welding transformer so that both were of the same polarity (see Fig. 13c, page 412).

Although the type 430 stainless steel had an electrical conductivity of 3% IACS, as compared to 14.5% for the low-carbon steel, and was somewhat thinner, no problems were encountered in obtaining satisfactory

heat balance, using the electrodes shown in Fig. 20.

The total cycle time for making a pair of spot welds, including indexing time, was 39 cycles. Thus a 5½-in.-long circular seam of 80 individual spot welds about 3/32 in. in diameter, each with about 35% overlap of the preceding spot, was completed in 26 sec.

With the improved joining method, production rate was almost eight times that of the original method, and cost for direct labor and material was only one-tenth as much. The assemblies joined by overlapping spot welds were leak tested at a pressure of 5 psi, and rejection rate was 0.5%. Additional equipment details and welding conditions are given in the table that accompanies Fig. 20.

Roll Spot Welding

Resistance roll spot welding consists of making a series of separate, spaced spot welds in a row by means of resistance seam welding machines and electrode wheels. The roll spot welds are made without retracting the electrode wheels or removing the electrode force between spots.

Current, welding time and electrode force are essentially the same as for resistance spot welding of similar workpieces. An individual roll spot weld has the same appearance as a spot weld made in the usual manner, except that the weld nugget is usually slightly elongated in the direction of electrode travel.

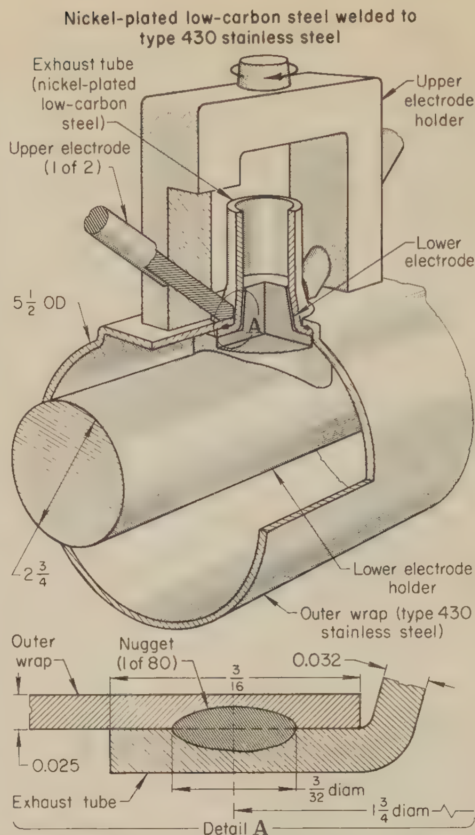
Roll spot welds are made using either continuous or interrupted motion of the electrode wheel, depending on the weld time needed to develop the necessary heat, and the hold time needed to solidify the weld metal (with continuous motion of the electrode wheel, hold time is zero). The desired weld spacing is obtained by adjustment of the electrode-wheel speed and of the current on and off times.

Nugget width (transverse to direction of travel) is determined primarily by the contacting width of the periphery of the electrode wheel. When electrode motion is continuous during welding, nugget length is a function of electrode diameter, rotation speed and heating time; when interrupted electrode motion is used, nugget length depends mainly on wheel diameter and heating time. For some roll spot welded assemblies (for example, the one shown in Fig. 21), nugget width may be governed chiefly by the shape and dimensions of one of the components.

Design and arrangement of fixtures and electrodes must be coordinated to ensure accurate match-up and intimate contact of the workpieces at all weld spots for roll spot welding. Fixturing was of special importance in roll spot welding a circular seam in the example that follows, in which a steel ring was joined to the bottom of a sheet steel can.

Example 379. Roll Spot Welding for Which Change in Fixturing and Method Reduced Rejection Rate and Increased Production (Fig. 21)

Roll spot welding was used for attaching a 15 21/32-in.-OD skid ring of ½-in.-diam low-carbon steel rod to the 0.048-in.-thick low-carbon steel bottom of a general-purpose can (see view at upper right in Fig. 21). The ring reinforced the sheet-metal bottom and provided a solid surface on which to move and store the can.



Equipment Details

Welding machine	Press type, semiautomatic, air-operated
Rating at 50% duty cycle	50 kva
Rating of secondary circuit	32,500 amp
Transformer taps	Six
Electrode material	RWMA class 2
Electrode force, max	1000 lb
Heat control	Phase shift
Timing control	Synchronous

Welding Conditions

Transformer tap setting	3
Heat-control setting	87%
Electrode force	312 lb, each electrode
Squeeze time	11 cycles
Weld time	8 cycles
Hold time	12 cycles
Off (indexing) time	8 cycles
Load time	8 sec
Unload time	10 sec
Production per hour	88 assemblies(a)
Direct labor, hr per 1000 assemblies:	
Original method	55
Improved method	7

(a) The machine operator also ran another resistance welding machine on which other types of assemblies were welded.

Use of overlapping spot welds increased production and reduced cost, compared with original method (spot welding plus silver brazing).

Fig. 20. Setup for joining a car-heater subassembly with 80 overlapping spot welds, to make an airtight joint (Example 378)

In the method originally used, the assembly was tack spot welded before being roll spot welded. For tack welding, the ring was held in position on the bottom surface of the can by a locating fixture (see upper left view in Fig. 21) and then was tack spot welded to the bottom in four places. After removal of the fixture, the assembly was placed in a circular seam welding machine that had one electrode wheel contoured to hold the ring and a flat-face electrode wheel that contacted the can bottom, and 65 roll spot welds were made around the ring.

Rejection rate was unacceptably high because a number of the welds on a significant percentage of assemblies were weak. It appeared that the fixture used for tack welding did not provide sufficiently accurate alignment between the can bottom and the skid ring. Under these conditions, the electrode force was not sufficient to bring the components into intimate contact for all welds during roll spot welding.

The tack and roll spot welded assembly was dropped from a height of 3 ft onto a concrete platform to test the soundness of the welds, which was determined by the ringing sound made when the assembly struck the platform. An assembly with some loose spot welds sounded noticeably different from one with all sound welds. After testing, the assemblies were hot dipped in a galvanizing bath at 860 F. Some of the spot welds that had previously been passed came apart in this operation, during which the more rapid heating and cooling of the sheet-metal bottom than of the thicker ring produced high local stresses at the welds and caused weaker welds to fail. Over-all rejection rate was 4½% — more than twice the plant standard maximum acceptable rejection rate of 2%.

A new roll spot welding fixture was designed that would eliminate the need for preliminary tack spot welding. The new fixture, shown at lower right in Fig. 21, was equipped with two sets of guide rolls. One set guided the can bottom at its periphery; the other set, which engaged the skid ring, supported the assembly at the proper level for the spot welding electrode rolls. Thus, the assembly was not removed from the fixture until all 65 spot welds were made.

The rigid new fixture held the components in accurate alignment and permitted intimate contact for all 65 spot welds. Use of the new fixture and technique, plus tightening of control over all operating variables, eliminated the preliminary tack welding operation and at the same time improved weld quality and reliability substantially. Over-all rejection rate was reduced from 4½% to between 0.1 and 0.4%.

Elimination of the extra handling operation increased production from 70 to 88 assemblies per hour, and the over-all improvement allowed a reduction of more than 20% in the price of the finished cans.

Tack welding, in the original method, was done with a single-phase alternating-current foot-operated spot welding machine rated at 50 kva (at 50% duty cycle). Roll spot welding, in both the original method and the improved method, was done with a single-phase alternating-current circular seam welding machine with 150-kva rating (at 50% duty cycle) and electronic controls. Heat-control setting in the improved method was 79%.

Spot Welding of Coated Steel

Low-carbon steel sheet that has been coated, by hot dipping, electroplating or other processes, with corrosion-resistant metals or alloys (such as zinc, aluminum, tin, and tin-zinc) is spot welded in large-scale production, as described in the next three sections of this article. Terne-coated steel (steel coated with a lead-tin alloy) is spot welded in large volume in making automobile mufflers, but otherwise not many individual plants use spot welding on this material.

Steel sheet with metallic coatings (such as nickel and chromium plating) that are intended to serve primarily as decorative coatings can be spot welded, sometimes (depending on plating thickness and properties) under the same welding conditions as those used in welding uncoated steel. However, because of the need to avoid marking of decorative surfaces, spot welding of steel that has been plated for this purpose is relatively infrequent.

Steel that has been electroplated with a functional (not decorative only) coating of another metal is spot welded in some high-production applications. For instance, nickel-plated steel is spot welded for use in electrical equipment, principally for terminals or contacts.

Steel sheet with phosphate or other conversion coatings is not ordinarily spot welded without removing the coating first. The high electrical resistance of these nonmetallic coatings (which varies with type and thickness of coating) makes it necessary to use high electrode forces and also may cause excessive sparking from between the workpieces when the flow of welding current is initiated. Variation in the thickness of a coating affects its electrical resistance and may interfere with welding. Also, the electrode tips may become badly pitted, requiring frequent cleaning and reconditioning, and particles of coating material may be intermixed with the weld metal.

Steel sheet is not ordinarily resistance spot welded through paint or plastic coatings on a production basis. However, techniques that use specially designed and operated electrodes to heat and penetrate organic coatings have been used with success in volume production (see Example 421, in the article on Resistance Welding of Copper Alloys, and Example 399, in the article on Projection Welding). The coating is softened at the weld site, and is displaced into the immediately adjacent areas of the work.

Spot Welding of Zinc-Coated Steel

Direct spot welding (see circuits in Fig. 13) is recommended for zinc-coated steel (which may be either hot dip galvanized or electroplated), because the shunting current associated with series welding, when added to the higher-than-normal current needed to weld zinc-coated steel, results in excessive electrode heating and short electrode life. When large panels are welded, the welding machine can be set up as shown schematically in Fig. 13(e) to reduce the throat depth.

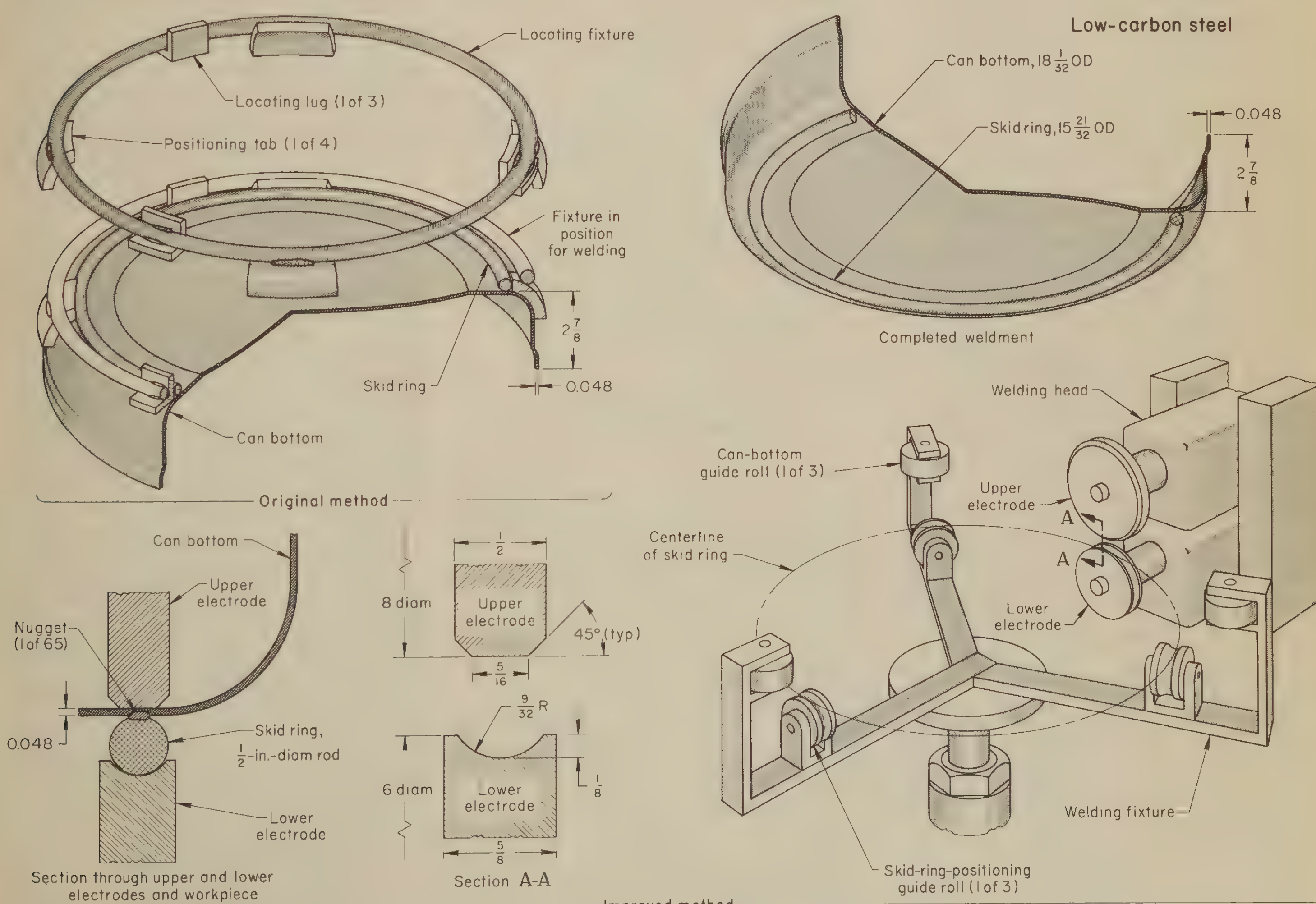
Weldability of thin sheets electroplated with zinc decreases as the coating thickness increases, in the range of 0.0002 to 0.001 in. However, as thickness of sheets increases above 0.060 in., weldability increases regardless of coating thickness. The welding behavior of hot dip galvanized steel is affected by the thickness and uniformity of the zinc-iron alloy layer, as well as the thickness of unalloyed zinc.

Electrode Design. Truncated-cone (type E) electrodes (see Fig. 9) are recommended for spot welding zinc-coated steel. The included angle of the cone should be from 120° to 140°, with the smaller angle being used where fit-up problems exist. The face diameter of the electrode should be four to five times the thickness of the thinner sheet for two-thickness welds. A larger face diameter requires greater current and results in shorter electrode life.

Flat-face (type C) electrodes are not recommended, because the melted zinc forced from the weld area forms an annular deposit on the electrode body surrounding the face. As the thickness of this deposit increases, the weld quality decreases.

When portable welding guns are used, a type F electrode having a radius of 1 to 2 in. is recommended. A smaller radius can result in increased indentation, and a larger radius in reduced electrode life.

Electrode Composition. RWMA class 2 (copper-chromium) electrode material generally provides the best electrode life. A copper-zirconium alloy also produces good electrode life, provided it has been sufficiently cold worked to



Fixture used in original method held components only while four tack spot welds were made; tack welded assembly was then transferred to a circular seam welding machine for application of roll spot welds. Improved fixture positioned and held assembly for application of roll spot welds in circular seam welding machine, thus eliminating tack spot welding.

Fig. 21. Change in fixturing that reduced rejections and raised production in roll spot welding a skid ring to a can bottom (Example 379)

Table 7. Conditions for Resistance Spot Welding of 1010 Steel 0.040 and 0.125 In. Thick, With and Without Zinc Coating (a)

Welding condition(b)	Steel 0.040 in. thick: Zinc coated(c)	Steel 0.040 in. thick: Uncoated	Steel 0.125 in. thick: Zinc coated(c)	Steel 0.125 in. thick: Uncoated
Weld time, cycles (60 cps)	13	10	42	26
Welding current, amp	14,000	9500	20,000	19,000
Electrode force, lb	650	500	2000	1800
Minimum weld spacing, in.	0.75	0.75	2	1.75
Nugget diameter, in.	0.21	0.19	0.48	0.33
Minimum contacting overlap, in.	⅝	½	1⅛	⅞

(a) Data for zinc-coated steel are from AWS C1.3, "Recommended Practices for Resistance Welding Coated Low Carbon Steels". Data for uncoated steel are from Table 4 in the present article. All data are for welding with class 2 electrodes. (b) For joining two sheets of steel in each of the two thicknesses. (c) Coated with 1.25 oz of zinc per square foot of sheet size.

achieve the hardness needed to resist plastic deformation of the electrode face. The buildup of zinc on and around the electrode face is a problem with both copper-chromium and copper-zirconium alloys, and the electrodes must be cleaned or replaced at regular intervals.

Where weld appearance is important and electrode sticking must be avoided, class 1 material can be used. The high conductivity of this alloy reduces heating at the interface of the electrode and the work. Resistance to deformation is not as great as that of class 2 material.

Cooling of electrodes is ordinarily done with a minimum water-flow rate of 2 gal per minute; cooling requirements vary with electrode material and dimensions, work metal and zinc thickness, and the welding conditions. If the water temperature exceeds 85 F, the rate of flow to the electrode should be increased. Overheating of an electrode softens it, and deformation of the electrode face occurs. Also, the higher temperature of the electrode results in an accelerated alloying of the copper electrode material with the zinc coating on the work metal.

Welding Conditions. To produce nuggets of adequate size in zinc-coated steel, longer weld times (25 to 50% longer) and higher currents are required than for uncoated low-carbon steel. Also, the range of welding times is narrower for zinc-coated steel.

The welding current can be as much as 50% greater than that required for uncoated steel, depending on work-metal thickness. Thinner work metals require proportionately higher currents than do thick metals.

The electrode forces used for welding zinc-coated steel are 10 to 25% greater than those used for welding uncoated steel. The increase in electrode force is necessary because the coating reduces the faying surface contact resistance to almost zero; also, the softened zinc must be extruded from between the sheets as quickly as possible, lest the base metal be softened.

To produce true welds of steel to steel, which must be done for strength greater than that of a soldered-type joint, the welding conditions must be such as to melt the zinc completely between the faying surfaces of the workpieces, over an area approximately the size of the electrode face, and to squeeze out this molten zinc in this weld-nugget area. Melting of the zinc on the surfaces of work in contact with the electrodes should be avoided if possible, to minimize electrode alloying and sticking, and to retain a uniform layer of zinc on the exposed work surfaces for corrosion resistance. The hold time should be of sufficient duration so that cooling by the electrodes continues long enough to avoid melting of the zinc on the work surfaces in contact with the electrodes, from the residual heat in the nugget and adjacent portions of the steel, and to allow any molten zinc in the vicinity of the weld to resolidify before the clamping force is released. The use of upslope and downslope of the welding current is sometimes helpful in producing the desired weld characteristics.

Table 7 compares welding conditions for 0.040 and 0.125-in.-thick 1010 steel coated with 1.25 oz of zinc per square foot of sheet size, with conditions for uncoated 1010 steel of the same two thicknesses.

For welding heavy-coated steel (1.50 oz of zinc per square foot), weld time must be increased by up to 45% over that used for welding commercial-coated steel (1.25 oz per square foot), or welding current increased by up to 10%. For welding light-coated steel (0.9 oz per square foot), weld time is decreased by 5 to 10% from that used for welding commercial-coated steel, or welding current decreased by up to 5%. (The nominal coating weights given here are based on sheet size, not on total surface of two sides; for coating weight per unit of surface area, multiply by two.)

Spot Welding of Aluminum-Coated Steel

Steel coated on both sides with aluminum in a hot dip process is available in two types. One type is coated with an aluminum-silicon alloy approximately 0.001 in. thick, and is used in high-temperature applications (up to 1250 F). The second type is coated with pure aluminum approximately 0.002 in. thick. Spot welds having good strength can be made on both types of aluminum-coated steel.

These coatings require high welding current, because they have high electrical and thermal conductivities. No special cleaning of the coating surface is needed. Grease and other foreign material should be removed by solvent cleaning or by a light pass with a power-driven wire brush.

The high welding current results in considerable heating at the contact surface between the electrode and the coated workpiece. The aluminum coating that forms on the electrode face can alter welding conditions, and therefore the machine settings may need adjustment after a few workpieces have been welded.

Electrodes with a type F (radius) face (see Fig. 9) and made of RWMA class 2 material are recommended. The radius of the electrode face should be 1 in. for sheet up to 0.025 in. thick, and 2 in. for sheet thicker than 0.025 in. The electrodes should be dressed with 160-mesh or 240-mesh aluminum oxide cloth after a predetermined number of welds have been made.

Welding Conditions. The weld time, welding current and electrode force are about the same as, or slightly greater than, those recommended for uncoated low-carbon steel. For work metal up to 0.030 in. thick, the welding current may be increased 15 to 25% over that used for uncoated low-carbon steel.

Spot Welding of Tin-Coated and Tin-Zinc-Coated Steel

Spot welding of steel with a tin or tin-zinc coating (hot dipped or electroplated) is done commercially. However, the machine settings are more critical than for welding uncoated low-carbon steel, and machines with low-inertia welding heads are recommended. Steel with a 0.0003-in.-thick coating of 80% tin and 20% zinc is easier to weld than a steel sheet coated with pure tin 0.0001 in. thick.

Electrodes with a truncated-cone (type E) face (see Fig. 9) and made of RWMA class 2 material are recommended. Class 1 electrode material gives good results in welding steel with tin or tin-zinc coating, but with shorter electrode life. Included angle of the cone should be 120°, and face diameter should be four to five times the thickness of the thinnest sheet.

Where marking of one sheet is undesirable, a large flat-face (type C; see Fig. 9) electrode can be used in contact with that sheet, and a radius-face (type F) electrode used with the second sheet, if the sheet thicknesses permit. Additional current is needed, because the current density is low. Greater indentation occurs on the second sheet, and electrode life is reduced. Initially, the electrodes may adhere to the surface of the sheet, but sticking decreases after a number of welds have been made.

Welding Conditions. Relatively short weld times are used, and the welding current should be adjusted so that there is no expulsion of steel from between the sheets. However, none of the tin or tin-zinc coating should be entrapped at the faying surfaces, and to prevent formation of solder-type joints, electrode force must be sufficient to extrude the melted coating before the base metal begins to soften. Optimum electrode pressure is about 10,000 psi; greater pressures cause indentation.

Spot Welding of Dissimilar Metals

Low-carbon steel can be resistance spot welded to most other ferrous metals and to many nonferrous metals, producing a weld nugget that is an alloy of the two metals.

In making a spot weld between dissimilar metals, a heat balance must be achieved that compensates for the differing properties of the two metals and results in the production of a weld nugget having approximately the same thickness on each side of the interface. More heat must be provided to the more thermally and electrically conductive metal, which generates less resistive heat and has greater loss of heat by conduction. The higher-melting of two dissimilar metals of approximately equal conductivity also needs more heat.

If two metals being welded do not differ greatly in conductivity, a satisfactory heat balance can be obtained by using an electrode of smaller face diameter, or an electrode fitted with a facing of higher resistivity (such as an RWMA group B electrode material), on the more conductive member of the joint. To compensate for a greater difference in conductivity between the two work metals, both techniques can be used simultaneously.

In a variation of the second technique described above (facing an electrode with a higher-resistivity material) the more conductive workpiece can be provided with a thin layer of a less conductive metal on its surface, either by a coating method such as electroplating, or by inserting a layer of poorly conducting foil between the workpiece and the electrode.

Another technique, which can be used alone or in combination with one or more of the methods just described, is to increase the thickness of the more conductive member of the joint.

Spot Welding vs Alternative Processes

For some applications, resistance spot welding is the only economical method for joining given workpieces. This was true for attaching brake flaps to a canister in Example 371, and for welding a large tractor fender in Example 372.

Under certain conditions, spot welding can replace riveting or bolting, or other welding methods. Because spot welding is a fast, efficient, low-cost joining method, it is sometimes used in the manufacture of highly competitive products such as disposable containers.

In the following example, to minimize cost, spot welding was used instead of gas metal-arc welding for joining attachments to a mass-produced disposable refrigerant container.

Example 380. Use of Spot Welding Instead of Gas Metal-Arc Welding To Minimize Cost (Fig. 22)

The two 0.045-in.-thick low-carbon steel shells shown in Fig. 22 were joined by means of an arc girth weld to form a disposable spherical refrigerant container with a capacity of 0.4 cu ft. This mass-produced container had to be both inexpensive and easy to handle, and because of the spherical shape, which was necessary for strength and structural stability, needed both a collar (to serve as a handle) and a stand.

On containers produced by other manufacturers, the stands either were three or four small bulges drawn into the bottom of the lower tank half or were foot rings attached by gas metal-arc welding; the collar was attached to the upper tank half by gas metal-arc welding or mechanically.

In considering spot welding as an alternative process for attaching the foot ring and collar, it was concluded that spot welding would provide savings in labor and supplies, and would result in a product equivalent to that joined by arc welding.

The 0.060-in.-thick collar and the 0.048-in.-thick foot ring were spot welded to the two tank halves, each of which had an inside spherical radius of 5³⁵⁄₆₄ in., before the tank halves were joined by girth welding. The electrodes were contoured so as not to damage the surface of the work. The upper (outer) electrode had an RWMA type E (truncated) face with a ¼-in.-diam flat; the lower (inner) electrode had a type F (radius) face with a 4-in. spherical radius. Both electrodes were of RWMA class 2 material, had RWMA No. 5 taper shanks and ⅝-in. body diameters, and were 3 in. long.

With these electrode contours, and the welding conditions shown in the table with Fig. 22, there was no expulsion of metal from the weld nugget, only slight denting of the outer tank-half surfaces, and no denting of the inner surfaces. Typical weld nuggets for the collar and the foot ring are shown in Fig. 22.

Two fixtures (not shown in Fig. 22) were used to position the collar and foot ring. The first of these was a ring to locate the collar with reference to a threaded spud (not shown in Fig. 22) that allowed access to the inside of the container. The second was a basket fixture that positioned the foot ring with reference to the equator of the container.

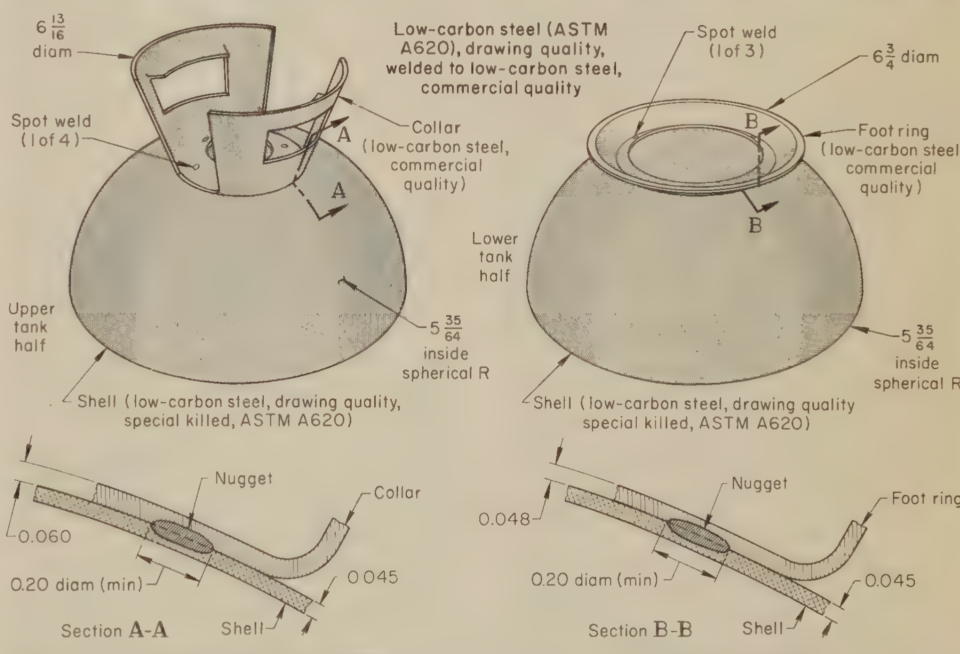
Production of the container was completed in the following steps:

1. The collar, foot ring, and tank halves were formed and vapor degreased.
2. The threaded spud was gas metal-arc welded to the upper tank half.
3. With the ring fixture located by the spud, the collar was positioned on the upper tank half and attached with four spot welds made one at a time, with the work manually located on the lower electrode.
4. The foot ring and lower tank half were placed in the basket fixture and were joined by three spot welds made one at a time, with the work manually located on the lower electrode.
5. The tank halves were then joined by girth welding by the gas metal-arc process. (See Example 81 in the article on Gas Metal-Arc Welding.)

All spot welds were visually inspected for weld soundness, and during each shift one production sample was destructively tested by twisting the collar from the upper tank half. These tests were made either by the operator or by quality-control personnel. The requirement for a satisfactory test was that the nuggets of all four spot welds be pulled away with the handle. The foot ring served only as a support and was not subject to large tensile loads, and the three welds attaching it to the lower tank half were evaluated by visual inspection only.

When spot welding was used to attach the collar and the foot ring, one operator could prepare enough completed upper and lower tank halves to supply a second operator running two girth-welding lathes. Containers produced in this way were neater in appearance than those for which the attachments were joined to the tank halves by arc welding.

Because the arc welded joints and spot welded joints were made by different manufacturers, no direct cost comparisons could be made. However, it was estimated that

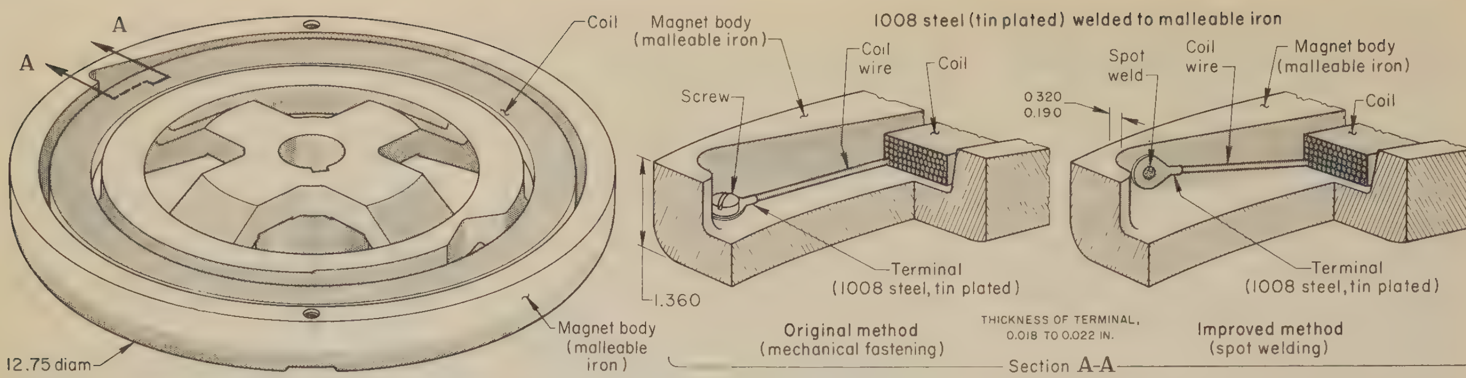


Equipment Details	
Welding machine	Rocker arm, air operated(a)
Rating at 50% duty cycle	50 kva
Rating of secondary circuit	14,200 amp
Transformer taps	Eight
Upper electrode(b)	Type E (truncated), ¼-in.-diam flat
Lower electrode(b)	Type F, 4-in. spherical radius
Electrode force, max	740 lb(c)
Controls	Nonsynchronous (NEMA N2H)

Welding Conditions	
Welding current	10,000 amp
Transformer tap setting	No. 4
Electrode force	500 lb
Squeeze time	10 cycles
Weld time	11 to 14 cycles, single impulse
Hold time	10 cycles
Off time	To suit operator
Production rate:	
Containers per hour	125 to 175
Welds per hour	875 to 1225

(a) Throat, 8 by 30 in. (b) Electrodes were removed from machine for dressing as needed. Both had RWMA No. 5 taper shanks and ⅝-in. body diameters, were made of RWMA class 2 material, and were 3 in. long. (c) Maximum electrode force at an air pressure of 80 psi.

Fig. 22. Components of a mass-produced disposable pressurized refrigerant container for which, to minimize cost, spot welding was used in preference to gas metal-arc welding for attaching a formed collar (handle) and a formed foot ring to the two tank halves, before joining halves by gas metal-arc welding as described in Example 81 on page 92 (Example 380)



Details of Equipment for Improved Method

Power supply	230-v, single-phase, 60-cycle ac
Welding machine	Portable push-type gun, mechanically operated
Rating at 50% duty cycle	15 kva
Rating of secondary circuit	8200 amp, 2 v
Electrodes	Type A (pointed), ⅛-in.-diam flat, No. 4 taper, RWMA class 2
Electrode force, max	1000 lb
Controls	Solid-state synchronous with voltage regulator

Operation	Original method	Improved method
Processing Times, Hours per 100 Magnets		
Drill and tap	3.320	0
Assemble and screw	2.050	0
Position terminal to side of housing	0	0.084
Position gun and weld	0	0.419
Release and return gun	0	0.032
Total standard hours	5.370	0.535
Time per magnet	3.22 min	19.26 sec(a)

(a) Includes 0.75 sec squeeze time, 0.50 sec weld time, and 0.50 sec hold time.

Fig. 23. Electromagnet for which tin-plated steel ground terminal of coil was spot welded to malleable iron magnet body, or housing, in 10% of the time needed for original method, mechanical fastening with a screw (Example 381)

labor expenditure was much lower for the spot welds than for the arc welds used to attach the handle and foot ring, and that the cost of supplies for arc welding (electrode wire and protective gases) was much greater than the cost of electrodes and electrode dressing for spot welding. Since the disposable containers were made in large quantities, amortization charges on the welding equipment were only a small fraction of the unit welding cost, and thus had little effect on process selection.

Spot Welding vs Bolting. Resistance spot welding frequently can be used for attaching items that need not be replaceable. It is the welding process most frequently used in place of mechanical fastening with screws or bolts for attaching electrical connectors when a permanent connection is desired. Bolting requires drilling, and sometimes tapping, of a hole, but a spot weld usually is completed in a fraction of a second.

In the following example, assembly time was greatly reduced when mechanical fastening with a screw was replaced by spot welding to make a permanent electrical connection.

Example 381. Change From Mechanical Fastening to Spot Welding To Reduce Time (Fig. 23)

Originally, the tin-plated 1008 steel ground terminal of an electromagnet coil was joined to the malleable iron body, or housing, of the magnet by mechanical fastening with a screw (see "Original method" view in section A-A in Fig. 23). This required drilling and tapping a hole, assembling the terminal to a screw, and turning the screw into the tapped hole.

The location of the ground terminal in the magnet body was not critical, and the terminal was repositioned for attachment by spot welding, as shown in the "Improved method" view in section A-A in Fig. 23. The only preparation needed for the new method was setting up the spot welding machine — a push-type portable gun, which was hung vertically above the magnet so that it could be pulled down quickly to complete the weld.

Equipment details and welding conditions are given in the table that accompanies Fig. 23, along with a comparison of the time needed for attaching the terminal to the housing by screwing and by spot welding. As shown in the table, the change to spot welding reduced the assembly time per magnet by 90%. Cost of the new equipment needed for spot welding was $550.

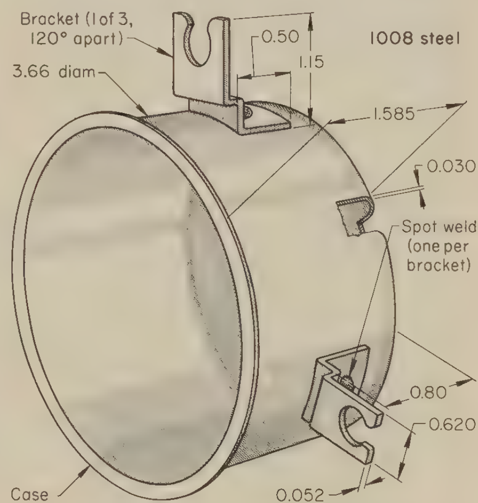


Fig. 24. Clock case for which method of attaching three brackets was changed from riveting to spot welding (Example 382)

Spot Welding vs Riveting. Spot welding can be done rapidly and is competitive with, and sometimes superior to, bolting or riveting as a method of attaching fittings to small housings such as those used in household and automotive electrical equipment.

In the following example, spot welding was found to cost less, and to provide stronger and more accurate fastening, than was possible with the former riveting method for joining brackets to a clock case.

Example 382. Change From Riveting to Spot Welding for Attaching Mounting Brackets (Fig. 24)

Figure 24 shows a clock case with three brackets that were used for mounting the clock to an external panel or a decorative housing. Originally, the brackets had been joined to the case by riveting, but spot welding provided stronger and more accurate fastening, at less cost.

The clock case was made of 0.030-in.-thick drawing quality 1008 steel; the brackets, of 0.052-in.-thick 1008 steel.

After the case was drawn and the brackets were formed, the components were degreased in solvent. Then the brackets, one at a time, were manually positioned on the clock case and were spot welded. The resistance spot welding machine had a 20-kva rating at 50% duty cycle. The maximum rating of the secondary circuit of the machine was 21,000 amp at 3.2 volts.

The welded assemblies were inspected visually, and sample assemblies were tested to destruction in pull tests. A test was considered satisfactory if a slug of metal was pulled from one of the two components when they were separated.

Table 8. Examples of Resistance Spot Welding That Are Presented Elsewhere in This Volume

Example	Description
388	Spot vs projection welding for joining low-carbon steel brackets to panels
400	Spot vs projection welding of type 430 stainless to galvanized steel
401	Spot vs projection welding a galvanized steel handle to a can cover
405	Spot vs projection welding for joining galvanized or low-carbon steel plate to a doorjamb made of the same metal
409	PH 15-7 Mo stainless steel upper and lower face sheets welded to a corrugated core
419	Aluminum alloy 6061-T4 sheet welded to 6061-T6 extrusions, in press-type and portable machines
...	Aluminum alloy 3003 flange 0.102 in. thick welded to a 0.125-in.-thick pan by multiple-impulse welding
...	Aluminum alloy 2024-T3 sheet and rolled sections roll spot welded using dual electrode force
420	Copper alloy 110 (braided wire) spot welded to alloy 184 vs induction brazing for clean, distortion-free parts
421	Copper alloy 110 plastic-coated wire joined to pins using an auxiliary ac heating circuit to melt the plastic
422	Copper alloy 110 stranded wire spot welded to a coin silver (90 Ag – 10 Cu) ring instead of being soldered
423	Effect of composition of gold plating on nickel strip on weldability to copper terminal clad with BCuP-5
424	Copper alloy 172 to alloy 260; size and location of spot weld were critical for performance and life of switch.

Resistance Seam Welding

*By the ASM Committee on Resistance Welding of Steel**

RESISTANCE SEAM WELDING is a process in which heat caused by resistance to the flow of electric current in the work metal is combined with pressure to produce a welded seam (which normally is gastight or liquid-tight) consisting of a series of overlapping spot welds. Two rotating, circular electrodes (electrode wheels), or one circular and one bar-type electrode, are used for transmitting the current to the work metal. When two electrode wheels are used, one or both wheels are driven, to move the workpiece, by means of a gear-driven shaft or by a knurl or friction drive that contacts the periphery of the electrode wheel.

The series of spot welds is made without retracting the electrode wheels or releasing the electrode force between spots, although the electrode wheels may advance either continuously or intermittently. The magnitude of the current, the duration of current flow, the electrode force, and the speed of workpiece or electrode travel are all related, and must be properly chosen and controlled to produce a satisfactory resistance seam welded joint. The principles described on page 401 for resistance spot welding are applicable also to resistance seam welding.

Applications. Resistance seam welding can be applied to a variety of workpiece shapes. Girth welds can be made in round, square or rectangular parts by using two electrode wheels of suitable diameter.

Longitudinal welds can be made by using two electrode wheels, or by using one wheel and a mandrel (stationary bar) over which the wheel travels. When two electrode wheels are used, they can be mounted either on parallel shafts or, if necessary for workpiece clearance, on shafts at an angle to each other.

Most resistance seam welds are lap seam welds. However, by special techniques (discussed in the sections on butt seam welds and foil butt seam welds, on page 433), butt seam welds can be made by resistance heating the two abutting edges and lightly forging them together, or by placing foil strip on one or both surfaces adjacent to the joint before applying heat and force with the electrodes.

Advantages of resistance seam welding, as compared with resistance spot and projection welding, are:

1 Gastight or liquid-tight joints can be produced.
2 Overlap can be less than for resistance spot welds or projection welds, and seam width can be less than the diameter of spot or projection welds.

Limitations of resistance seam welding, apart from those it shares with spot and projection welding (see the articles on pages 401 and 434), are:

1 The weld ordinarily must proceed in a straight or uniformly curved line.
2 Obstructions along the path of the electrode wheel must be avoided or be compensated for in the design of the wheel.
3 Sharp corner radii or abrupt changes in contour along the path of the electrode wheel must be avoided.
4 Length of joints made in a longitudinal seam welding machine is limited by the throat depth of the machine.
5 Fatigue life of resistance seam welds is usually less than that for welds made by other seam welding methods.
6 Stock thicknesses greater than ⅛ in. are more difficult to weld than by spot or projection welding.

Metals Welded. Low-carbon, high-carbon, low-alloy, stainless, and many coated steels can be resistance seam welded satisfactorily. Aluminum, aluminum alloys, nickel, nickel alloys and magnesium alloys can be seam welded, but seam welding is not recommended for copper and high-copper alloys. Compatible combinations of dissimilar metals and alloys also can be seam welded.

For information on the seam welding of stainless steel, aluminum alloys, and copper alloys, see the articles that begin on pages 456, 466 and 475.

Preweld Cleaning. Resistance seam welding of surfaces contaminated with grease, paint, scale or rust results in nonuniform welds, porosity in the weld nugget, and excessive burning and marking of workpiece surfaces in the region of contact with the electrodes. It can also cause rapid deterioration of the electrode-wheel contact surfaces. Methods suitable for cleaning the surfaces of ferrous and nonferrous metals prior to welding are described in Volume 2 of this Handbook. See also the section on Effect of Workpiece Surface Condition on Heating, page 415 in the article on Resistance Spot Welding in the present volume.

Seam Welding Machines

A seam welding machine is similar in construction to a spot welding machine, except that one or two electrode wheels are substituted for the spot welding electrodes. Generally, seam welding is done in a press-type resistance welding machine with a means of driving the electrode wheels, or of moving the workpiece between the electrodes, and with a direct-acting air or hydraulic cylinder for supplying the required electrode force.

Most seam welding machines are powered by alternating current; some are designed for use with three-phase supplies, but a majority operate on single-phase alternating current. Stored-energy seam welding machines have been built, but this type finds little use.

Equipment needed for seam welding consists essentially of: (*a*) a power supply capable of delivering low-voltage, high-amperage current; (*b*) a means of supporting the electrodes and the workpiece, and of applying the electrode force; (*c*) a means of moving the workpiece or of driving the electrodes; and (*d*) controls for regulating, timing and sequencing the application of the welding current and force and the rate of movement of the work between the electrodes.

Power supplies used for resistance seam welding are similar to those used for resistance spot welding, and consist of a welding transformer (usually with a tap switch in the primary circuit) and a secondary circuit with electrodes for transferring the welding current to the work metal.

Electrode Force and Support. The upper electrode wheel is mounted to, and insulated from, the operating head. The head, which is actuated by a direct-acting air or hydraulic cylinder, applies the electrode force.

The lower electrode is either a wheel, a platen or a mandrel, and is mounted on a supporting arm, table or knee. The supporting element can be adjustable for applications in which the work metal must be maintained at a constant level above the floor.

Electrode or Workpiece Drives. Workpieces can be moved by rotating the electrodes with knurl or friction drive, with gear drive, or by clamping the workpieces to a bar electrode and moving the bar electrode.

In knurl or friction drive, one or both of the electrodes are rotated by a knurl or friction wheel on the periphery of the electrode wheel. With this type of drive, a constant linear speed is maintained, regardless of the diameter of the electrode wheel, and the electrode wheel is continuously trimmed by the drive wheel, and thus is prevented from mushrooming. Knurl drive, in which ridges or beads on the circumference of the roll-shape steel drive wheel aid in gripping the electrode, minimizes slippage and is more positive than friction drive, in which the gripping edge of the drive wheel is smooth. Knurl drive is used for welding scaly stock and coated metals such as galvanized steel and terneplate, or in any application where the electrodes are likely to pick up material from the work metal; the knurled wheel removes much of the pickup from the electrode wheels. Knurl or friction drive can be used only with electrode wheels that have a diameter large enough to allow clearance between the drive wheel and the workpiece. Knurl drive usually is not employed where the highest weld quality and appearance are required.

*For committee list, see page 401. Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees. Eight examples of resistance seam welding appear in other articles in this volume (see Table 4, page 434).

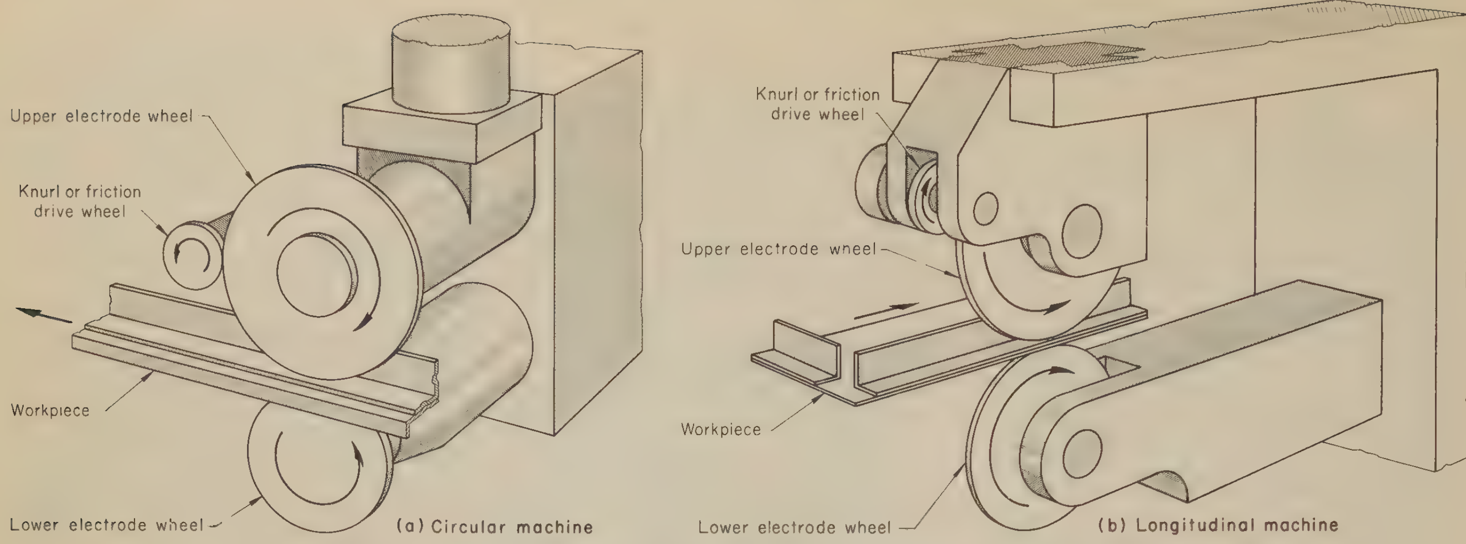


Fig. 1. Position of electrode wheels on circular and longitudinal resistance seam welding machines

Gear drive is used with small-diameter electrode wheels that cannot be driven by the use of knurled or friction wheels because of interference with workpiece clearance, or where the application cannot tolerate an electrode wheel that has been roughened by a knurled drive roll. With gear drive, in which the mounting shaft of the electrode wheel is rotated, there is no minimum limitation on electrode-wheel diameter. Normally, because of problems in synchronizing the speed of the two electrode wheels, only the lower wheel is driven. In a standard seam welding machine, there is a minimum distance between electrode-wheel centers, and if one wheel must be small to clear the workpiece, the other must be correspondingly large. If the ratio of the electrode-wheel diameters is greater than 2 to 1, the smaller wheel should be driven, to minimize slippage. As the diameter of the driven electrode wheel is gradually reduced by wear and by re-dressing, welding speed is decreased, reducing output and sometimes making it necessary to change the heat-control setting. Welding speed can be kept constant in spite of wheel wear by a variable-speed gear-drive mechanism.

When a mandrel or a platen is used as the lower electrode, the operating head carrying the upper electrode may be mounted in a carriage. The carriage is moved by an air or hydraulic cylinder, or by a motor-driven screw, and thus the upper electrode is passed over both the workpiece and the lower electrode. The upper electrode is free-wheeling, but it may be equipped with an idling knurl for dressing. In some machines, the workpiece is clamped to a bar-type lower electrode and moved under an idling fixed-position upper electrode wheel.

Controls for resistance seam welding are generally similar to those for resistance spot welding, except for those differences related to the relative motion of the work and the electrodes.

Because of the brevity of the heating and cooling (current on and off) cycles, a synchronous timing control connected to the primary circuit of the transformer is necessary for consistently accurate timing, unless the welding speed is such that the frequency of the welding current acts itself as an interrupter. A phase-shift heat control is also used, as well as tap switches for changing the transformer output.

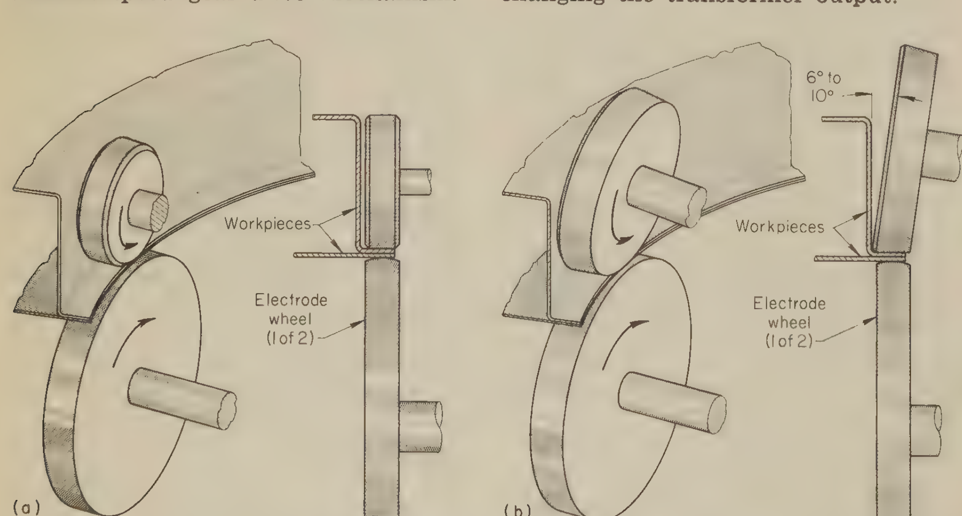


Fig. 2. Use of a small-diameter upper electrode wheel (a) *or of a canted larger-diameter upper electrode wheel* (b) *to avoid interference with a sidewall in welding a narrow flange along an inside radius*

Types of Machines. There are four basic types of resistance seam welding machines:

1. **Circular,** in which the faces of the electrode wheels are at right angles to the throat of the machine (see Fig. 1a). This type is used for circular work, such as welding the heads on containers, and for flat work requiring long seams.
2. **Longitudinal,** in which the faces of the electrode wheels are parallel to the throat of the machine (see Fig. 1b), and throat depth is typically 12 to 36 in. This type is used for welding short longitudinal seams in containers, for attaching pieces to containers, and for similar work. Machines with traveling heads or traveling electrodes, in which a mandrel or a platen is used for the lower electrode, are normally of the longitudinal type.
3. **Universal,** in which a swivel-type head and interchangeable lower arms allow the faces of the electrode wheels to be set either parallel or perpendicular to the throat of the machine.
4. **Portable,** in which the work is clamped in a fixture and a portable welding head is moved over the seam. This type of machine is used for workpieces that are too bulky to be handled by regular machines, and for applications where it is more efficient to move a portable welding head to the work than to move the work to the welding head on a regular machine. The portable welding head is moved by motor-driven wheels, and an air-cylinder mechanism provides the electrode force.

Because the arms of circular, longitudinal and universal seam welding machines are part of the secondary electrical circuit, the reactance of the secondary circuit and the welding current both are affected by the amount of magnetic material that passes between the arms, or through the throat, of the welding machine, unless automatic current regulators are included in the control circuit. The usable throat depth governs the size of workpiece that can be welded in a particular machine.

Electrodes

Electrode wheels made of RWMA class 1 material have been used for seam welding aluminum and magnesium alloys, galvanized steel, and tin-

plated steel. With adequate cooling, the high electrical and thermal conductivities of this material keep the electrode temperature below the point at which work metals such as aluminum readily alloy with copper from the electrode and cause electrode sticking or pickup.

High-production seam welding of low-carbon and low-alloy steels is usually done with electrodes made of class 2 or class 3 material. Class 3 materials have higher mechanical properties and lower electrical conductivity than do class 2 materials, and are used in applications where electrode pressure and workpiece resistance are high. In such applications, the resistance of the electrode wheel to deformation is more important than its electrical conductivity. (See Table 2 and page 409 in the article on Resistance Spot Welding for a description of the properties and use of RWMA electrode materials.)

Size of Electrodes. Electrode wheels range in diameter from 2 to 24 in. Table 1 shows the diameters and body widths of electrodes most often used, in relation to the size of the welding machine. Narrower wheels are used in machines with knurl or friction drive; wider wheels, in gear-drive and idler machines.

A small-diameter electrode wheel (Fig. 2a), or a large-diameter wheel mounted on a canted axis (Fig. 2b), can be used to avoid interference with a sidewall when a narrow flange is being welded on an inside radius or on a re-entrant curve. In both applications, the diameter of the opposing wheel must be adjusted in accordance with the spacing of the mounting shafts. Canting of electrode wheels usually is limited to 6° to 10°, to minimize the effect of this type of loading on the machine components. Larger angles can be used if the machine is suitably designed.

When the sides and ends of square or rectangular containers are being joined, welding of corners requires electrode wheels of different diameters. An electrode wheel with a radius smaller than the corner radius of the workpiece is used to contact the inside of the flange joint at the corners. Length of periphery in contact with the work metal at any instant is shorter for the outer wheel than for the inner wheel. The inner wheel is the driving wheel, and for this reason, as well as because of its shorter circumference, it has a shorter life than the outer wheel.

Beads, ribs and other extensions on the surfaces to be seam welded can be passed over by cutting notches in the electrode wheels, as shown in Fig. 3.

When thick work metal is being welded, the higher current and force requirements necessitate increasing the electrode face width (as shown in Table 3), to avoid excessive pressure and current density. Typical electrode face widths range from 3/16 to 1/2 in. for the wheel body widths listed in Tables 1 and 3. The width of a resistance seam weld is usually about 80% of the width of the electrode face.

Basic Face Contours. The four basic electrode-face contours in common use — straight flat, single-bevel flat, double-bevel flat, and radius — are shown in Fig. 4. Flat-face electrodes, although more difficult to set up, control and maintain than radius-face electrodes, may be necessary for welding certain workpieces. Electrode wheels must be of sufficient width (*W* in Fig. 4) to provide stability, but can be single or double beveled to provide a narrower contact surface (*w* in Fig. 4), and to minimize mushrooming of the wheel face. Radius-face electrodes, or one radius-face electrode used with one flat-face electrode, give good weld appearance, and aid in guiding the travel of the workpiece.

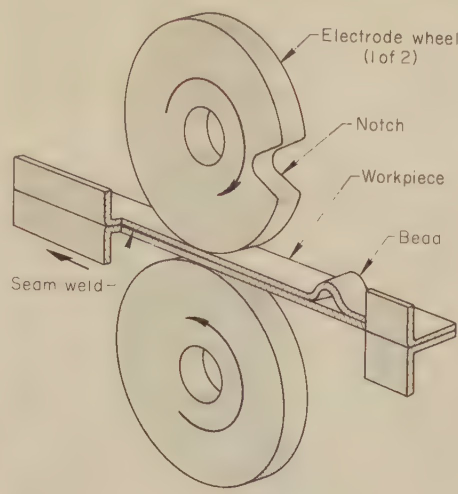


Fig. 3. Use of a notched electrode wheel for seam welding of a workpiece having beads (or other obstructions) in the path of the wheel (see also Fig. 11)

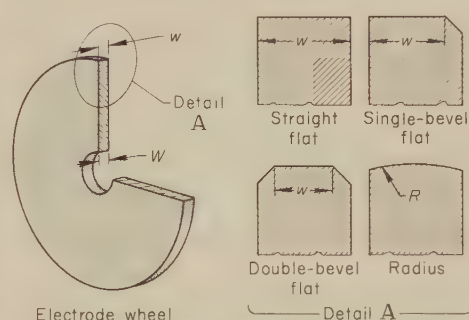


Fig. 4. Four basic types of faces on electrode wheels used for seam welding. (W is wheel width and w is the width of contact surface on flat or beveled wheels.)

Table 1. Common Sizes of Electrode Wheels Used for Resistance Seam Welding

Machine size	Wheel diameter, in.	Wheel width, in.(a)
Small	7	3/8
Medium	8	3/8 to 1/2
Large	10 to 12	3/8 to 3/4

(a) Data are for body width; see Fig. 4 and footnote (c) in Table 3.

Cup-shape electrodes, mounted on a canted axis (see Fig. 5), are used for upper electrodes in applications requiring small-diameter ring-type seam welds. The axis gyrates in a cone-shape path, bringing succeeding areas of the face of the moving electrode into contact with the work. The angle at which the axis is canted and the diameter of the cup-shape electrode determine the diameter of the seam weld that can be obtained. With this arrangement, the work is engaged by the axial face, and not by the periphery, of the electrode. The design of the lower electrode depends on the workpiece; Fig. 5 shows an annular lower electrode used, with a cup-shape upper electrode, for welding a flanged workpiece.

A disadvantage of a gyrating cup-shape electrode is that it may skid and cause distortion of the work metal, especially when welding thin material.

Bar electrodes, which are made of the same materials as electrode wheels, are used as lower electrodes in conjunction with upper electrode wheels.

The size and shape of a bar electrode depend on the size, shape and arrange-

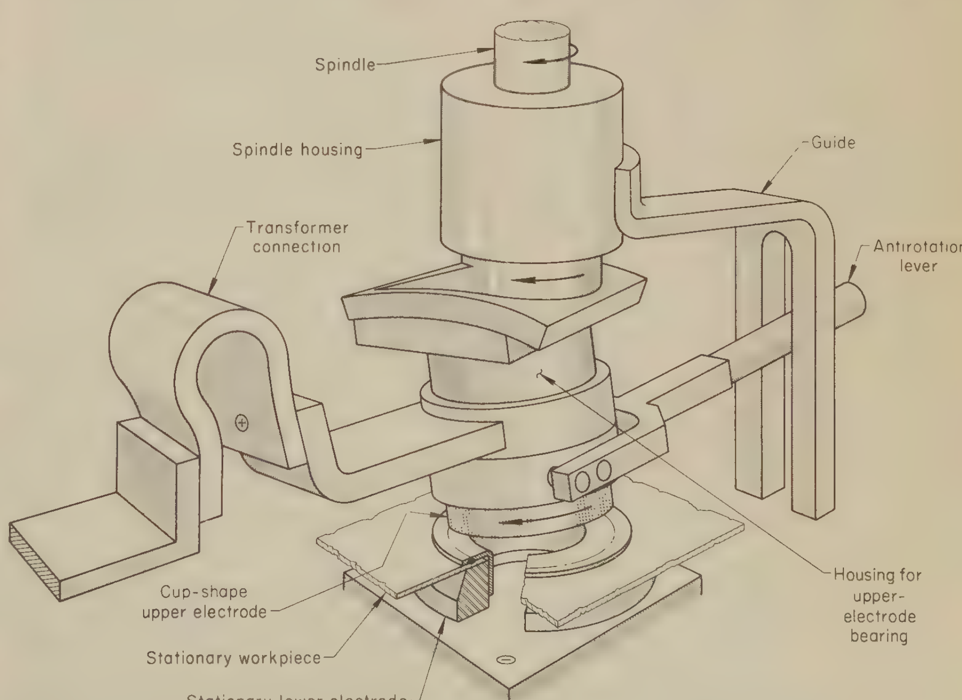


Fig. 5. Use of a free-rotating cup-shape upper electrode mounted on a canted axis for making a flat circular seam weld

ment of the work. In Example 387, the lower electrode was a conforming bar mounted in a mandrel that provided internal support for a hollow workpiece.

Cooling of electrodes and work during welding is mandatory. It is usually done by flooding or by directing jets of water on the electrodes and the work. (In welding low-carbon steel, a 5% borax solution is sometimes used to minimize rusting.) In applications where such cooling techniques have adverse effects on workpieces, mounting shafts can be cooled, and internally cooled electrodes can be designed. Inadequate cooling results in overheating of the work metal and shortening of the life of the electrodes.

Maintenance of wheel contour within established limits is essential to the control of current density, electrode pressure, and consistency of weld quality. Only light cleaning of the electrode face should be done while the electrode is in the machine. Dressing the electrode wheel in a lathe after a predetermined number of welds or feet of weld seam have been made maintains a uniform contour, saves electrode material and reduces the number of rejected workpieces.

Knurl drive provided continuous electrode-wheel dressing in Example 385, which describes the semiautomatic resistance seam welding of a sump to a washer tub. Automatic wheel dressers have been used in large high-production machines, such as those used in seam welding of roof decking. The use of knurl or friction drive or of automatic wheel dressers does not necessarily ensure removal of pickup; the electrode wheels should be periodically inspected to determine the need for supplementary, off-machine dressing.

Methods of Welding

In resistance seam welding, a series of overlapping spot welds is made by either continuous or intermittent motion of the electrode wheel or wheels and the work, and by suitable application of welding current. The type of motion used depends on work-metal thickness, welding speed and weld spacing.

Continuous motion is used for joining workpieces less than about 3/16 in. thick. Optimum electrode-wheel speed depends on wheel diameter, cooling methods that are available or permissible, and the thickness and surface condition of the work metal. For a given cycle of heat and cool time, the peripheral speed of the electrode wheel determines the number of welds per inch, and therefore the tightness of the joint. Table 2 lists the number of spot welds per inch needed to produce a gastight seam in various thicknesses of low-carbon steel. The application of the welding current can be either continuous or interrupted (see the section on Effect of Welding Current).

Table 2. Approximate Number of Spot Welds per Inch Needed To Produce a Gastight Seam in Low-Carbon Steel

Thickness of one sheet, in.	Number of spot welds per inch	Thickness of one sheet, in.	Number of spot welds per inch
0.010	18 to 24	0.051	12 to 14
0.016	16 to 20	0.064	11 to 13
0.020	15 to 18	0.081	10 to 12
0.025	14 to 16	0.102	9 to 11
0.032	12 to 14	0.125	8 to 10

Intermittent motion is used for joining metals more than 3/16 in. thick, or where postheating or forging cycles are used. The electrode wheels are stopped as each spot weld is made, and then are automatically rotated to move the work the proper distance for the next weld. A synchronous precision electronic timer or a solid-state nonsynchronous timer is recommended for controlling the electrode motion and the application of current. Mechanical timers are slow, nonsynchronous, and otherwise inaccurate, and are not recommended.

Control of Welding Conditions

Welding current, electrode force, heat time, cool time and welding speed all directly affect weld quality, and must be carefully controlled. A compromise among variables is often necessary in defining welding schedules. The amount of heat generated can be controlled either directly by increasing or decreasing the welding current, or indirectly by increasing or decreasing the electrode force, which affects the contact resistance.

As in resistance spot welding, the main factors that influence the selection of welding current and electrode force are: (*a*) the required nugget size, which is related to weld strength; (*b*) the probability of porosity; and (*c*) the desired surface condition of the finished weld. The factors that influence the selection of heat time, cool time and welding speed are: (*a*) the ability of the operator, or of the material-handling equipment, to handle the workpiece during welding; (*b*) the nugget size; (*c*) the extent to which weld nuggets must overlap to ensure pressure-tight joints; and (*d*) the probability of electrode pickup.

Recommended practices for resistance seam welding of low-carbon steel are given in Table 3. The values listed are starting conditions and should be adjusted to suit the application.

Table 3. Recommended Practices for Seam Welding of Low-Carbon Steel(a)

Thickness (t) of thinnest outside piece, in.(b)	Electrode dimensions, in.(c): Wheel width, W	Electrode dimensions, in.(c): Face width, w	Net electrode force, lb	Heat time, cycles (60 Hz)	Cool time (pressure tight), cycles (60 Hz)	Welding speed, in. per min	Welds per in.	Welding current (approx), amp	Minimum contacting overlap, in.(d)
0.010	3/8	3/16	400	2	1	80	15	8,000	3/8
0.021	3/8	3/16	550	2	2	75	12	11,000	7/16
0.031	1/2	1/4	700	3	2	72	10	13,000	1/2
0.040	1/2	1/4	900	3	3	67	9	15,000	1/2
0.050	1/2	5/16	1050	4	3	65	8	16,500	9/16
0.062	1/2	5/16	1200	4	4	63	7	17,500	5/8
0.078	5/8	3/8	1500	6	5	55	6	19,000	11/16
0.094	5/8	7/16	1700	7	6	50	5.5	20,000	3/4
0.109	3/4	1/2	1950	9	6	48	5	21,000	13/16
0.125	3/4	1/2	2200	10	7	45	4.5	22,000	7/8

SOURCE: "Recommended Practices for Resistance Welding", AWS C1.1; also "Welding Handbook", 6th Ed., Section 2, American Welding Society, 1969. Published here by permission.

(a) Data are for 1010 steel; material should be free of scale, oxides, paint, grease and oil. Welding conditions are determined by thickness of thinnest outside piece. (b) Data for total thickness of pile-up not exceeding 4t. Maximum ratio between thicknesses, 3 to 1. (c) For RWMA class 2 electrode material (minimum conductivity, 75% IACS; maximum hardness, Rockwell B 75). Wheel width is over-all width of a flat-face wheel or of a wheel with a 3-in.-radius face; face width is that of the contacting surface of flat-face wheels (see Fig. 4). (d) For large assemblies, minimum contacting overlap indicated should be increased 30%.

Setting up Welding Schedules. The sequence of steps followed in setting up a resistance seam welding schedule may vary, depending on special aspects of the equipment or the work, the extent of experience with similar types of work, and requirements imposed by the purchaser or applicable specifications. A typical sequence of steps for determining the most satisfactory conditions for resistance seam welding for which previous experience is lacking is as follows:

1. **Make a preliminary selection of welding speed and electrode force** that represent practical working values and are not near the upper or lower limits of the welding-machine capability. The recommended practices that are shown in Table 3 may provide starting points for this selection, as well as guidance in choosing preliminary values of heat and cool times and welding current for making trial welds.
2. **Establish criteria for satisfactory welds,** based on the requirements of the specific application. Generally, the weld nugget should have no porosity, nugget overlap should be about 15 to 20% of nugget length to yield leaktight seams, and nugget penetration should average 45 to 50% of the thickness of the thinnest sheet but be within the limits of 30 to 70%.
3. **Select Heat and Cool Time.** This is done by evaluating test welds made at several welding currents for each of a number of combinations of heat and cool times. Welding speed and electrode force are those provisionally chosen in step 1.
4. **Select Electrode Force.** Using the provisionally chosen welding speed and heat and cool times, make welds at several different currents, using a number of values of electrode force to cover a range of force.
5. **Select Welding Current.** Using the provisionally chosen welding speed, heat and cool times and electrode force, make test welds at various welding currents that cover a wide range of current.
6. **Select Welding Speed.** Using the provisionally chosen other welding conditions, make test welds with welding speeds that cover a wide range. The welding speed selected should yield suitable nugget overlap, penetration with negligible indentation or surface pitting, and no porosity. Also, the speed should be such that the operator can control the travel of the workpieces between the electrodes.
7. **Verify Selection of Conditions.** Make test welds under the provisional welding conditions to verify these selections and to establish reference data on weld quality and reliability for process control. A more complete evaluation than for steps 1 to 6 is done at this stage, and ordinarily involves detailed metallographic examination, as well as the usual measurements on macrosec-

tions of welds. Depending on the application, nondestructive examination may also be done, using radiography and ultrasonic, sonic and eddy-current techniques.

The seven steps described above not only determine optimum values for each of the welding variables, but also establish ranges of satisfactory values for them and the criticality or noncriticality of each.

If the results of the test welds in step 7 are not satisfactory, the seven-step procedure may be repeated, making changes in the welding conditions as indicated by the test results. Changes in welding equipment, electrode material and electrode design may also be made at this time, although these are ordinarily well-determined in advance. If a change in machines or electrodes is necessary, the seven-step procedure (or parts of the procedure) should be repeated until acceptable results are obtained.

When adjustment of welding conditions is needed at the start of or during production runs, the adjustment is usually made on heat time, cool time or welding current, whichever is most convenient and effective. No adjustments outside the acceptable ranges determined in the development of the welding schedule should be made without special qualification by the evaluation of a suitable number of trial welds.

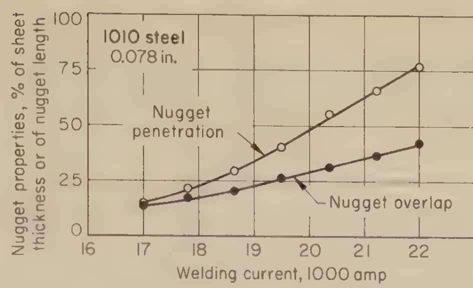
Sufficient cooling water should be used to cool the electrodes and the workpiece; nonuniform cooling results in the production of asymmetrical weld nuggets. The effects of varying amounts of magnetic material (either in the welding fixture or the workpiece) in the throat of the welding machine also must be considered in establishing welding conditions.

Welding of a corner arc is more difficult than welding of straight sections, especially when the corner radius is small; different and more closely controlled operating conditions generally are needed for optimum weld quality, and usually involve decreased welding speed. When the corner radius is large and quality requirements are not unduly critical, machine settings based on welding of the corners may also be satisfactory for the straight sections.

Where the same machine settings will not produce an acceptable seam weld on corners and straight sections, a two-speed control or automatic changing of heat settings can be used. The two-speed system permits taking advantage of the higher welding speed possible on straight sections.

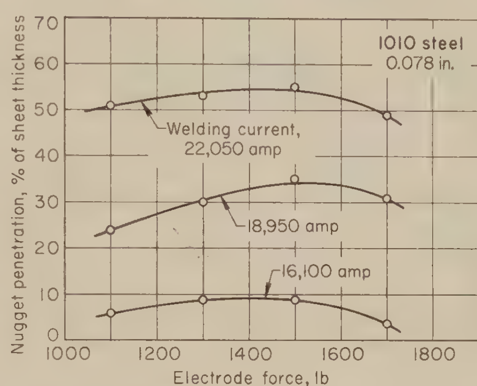
Quality Control. General practice in quality control in resistance seam welding is similar to that described for resistance spot welding, beginning on page 417.

One test method that is not applicable to spot and projection welding but is especially useful in evaluating seam welds is pressure testing to determine if seams are liquid-tight or gastight. A standard method for pressure testing of resistance seam welds is the pillow test. (This test was used in obtaining the data on joint strength plotted in Fig. 10.) For a comprehensive discussion of the pillow test and other standard methods for testing resistance welds, the reader is referred to Section V in AWS C1.1-66, "Recommended Practices for Resistance Welding".



Welding conditions: heat time, 6 cycles; cool time, 5 cycles; electrode force, 1500 lb; and welding speed, 55 in. per minute. (SOURCE: RWMA Bulletin 23)

Fig. 6. Effects of welding current on nugget penetration and nugget overlap in seam welding 0.078-in.-thick 1010 steel



Welding conditions: heat time, 6 cycles; cool time, 5 cycles; welding speed, 55 in. per minute. (SOURCE: Same as Fig. 6)

Fig. 7. Effects of welding current and electrode force on nugget penetration in seam welding 0.078-in.-thick 1010 steel

Effect of Welding Current

In resistance seam welding, much as in resistance spot welding, heat is generated by resistance to the flow of electric current (*a*) at the contact interfaces between the electrode wheels and the surfaces of the workpieces; (*b*) in the work metal itself; (*c*) at the interface of the workpieces; and (*d*) in the electrodes.

The points of heat generation and temperature gradients after 20% and 100% of weld time in electrodes, workpieces and nugget during the formation of a spot weld are shown in Fig. 14 on page 413 in the article on Resistance Spot Welding. For a more complete discussion, see the section on Effect of Welding Current on Heating, page 412.

For a given heating-and-cooling cycle and a given welding speed, the magnitude of the current determines the depth to which the weld metal penetrates the base metal and the amount that the individual nuggets overlap. The effects of welding current on nugget penetration and nugget overlap in welding 0.078-in.-thick 1010 steel are shown in Fig. 6. (See also Fig. 7 and 8, which show, respectively, nugget penetration and nugget width obtained at three levels of current.)

In welding low-carbon steel, the average nugget penetration should be within 30 to 70% of the sheet thickness, with 45 to 50% as optimum. For leaktight seams, nugget overlap should be 15 to 20% of nugget length.

Welding-current values in excess of those giving full joint strength increase nugget penetration and nugget overlap, but do not add to joint strength, and are uneconomical. Also, they can cause excessive indentation and, if extreme, burning of the weld. Generally, resistance seam welded joints are sufficiently strong that test samples fail in the heat-affected base metal adjacent to the weld.

Continuous alternating current with partial wave form and interrupted current are both used for resistance seam welding. Continuous current can be used for high-speed operation, or where the wave form can be adjusted to produce the proper nugget size and spacing at the available welding speed. Interrupted current is used for most seam welding operations, and offers the following advantages:

1. Better control of heat
2. Provision of time between each spot weld in the seam for cooling of each nugget under pressure
3. Less distortion of workpieces resulting from overheating of metal adjacent to the weld
4. More-uniform welds with fewer surface defects.

Welding current is selected by trial-and-error in relation to the other operating variables in developing a welding schedule (see list under "Setting up Welding Schedules" on page 428). With shorter heat times, or with faster welding speeds, more current is required and the probability of electrode pickup is greater. Currents higher than those used for spot welding are required for seam welding, because of the continuous shunting of the current through the preceding welds.

Effect of Electrode Force

The amount of heat generated in the weld can be controlled by varying the welding current, or to a lesser degree by varying the electrode force, which affects contact resistance. The selection of the proper electrode force limits the range of welding-current values that will produce satisfactory joints, and with low electrode forces, small variations in welding current have considerable influence on weld quality. Therefore, electrode force should be high enough to permit a wide variation in current values.

Up to a certain point, increasing the electrode force causes a slight increase in nugget penetration and nugget width, but beyond that point nugget penetration decreases while nugget width increases more rapidly. With increased electrode force, the welding current is more concentrated at the center of the weld because of the crowned electrode surfaces, but is distributed over a wider surface because of indentation. Thus, as nugget width increases, nugget penetration decreases.

The effect of the electrode force on nugget penetration in seam welding 0.078-in.-thick 1010 steel using three

different values of welding current is shown in Fig. 7. Heating time was 6 cycles, cooling time 5 cycles and welding speed 55 in. per minute. The effect of the electrode force on nugget width under the same welding conditions is shown in Fig. 8.

Electrode force must be sufficient to provide good electrical contact and thus permit flow of current through the circuit. To avoid low-quality welds in workpieces that do not fit-up properly, sufficient total force must be applied to bring the workpieces into contact and to maintain the force needed for welding. If the applied force is constant, variations in the force needed to bring the workpieces into contact will cause variations in the welding force, thereby affecting weld quality. Excessive electrode force results in severe indentation of the workpieces, rapid mushrooming of the electrodes, and large reduction of contact resistance, which requires an increase in current.

Insufficient electrode force results in improperly forged welds and in excessive contact resistance between the electrodes and the work, causing burning, and therefore short life, of the electrodes. It can also permit the expulsion of molten metal at the interface, thus (like excessive electrode force) resulting in surface indentation at the welded seam.

The pressure at the weld is constantly changing because of the rapidly changing temperature and strength of the metal in the heated area. For best results, the welding machine should be designed with a low-inertia follow-up system, which applies reactive force to the welding head to maintain the proper distance between the electrodes, and to avoid low pressure, high contact resistance, and expulsion of metal from the weld zone.

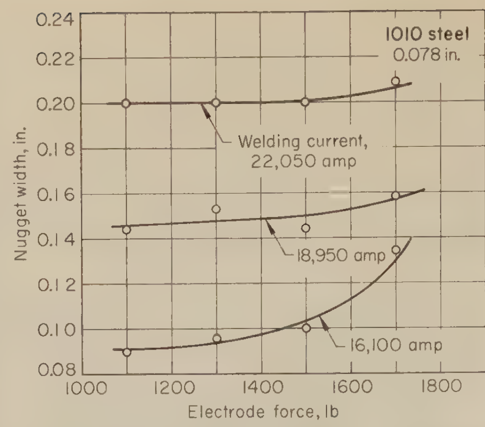
Effect of Heat Time and Cool Time

The nugget size is controlled principally by the heat time, and nugget overlap, by the cool time. For lower welding speeds, the ratio of heat time to cool time should be between 1.25 to 1 and 2 to 1 for best results. As welding speed increases, the spacing of the spot welds increases so that they do not overlap unless the ratio of heat time to cool time is increased: for example, at higher welding speed, a ratio of heat time to cool time of 3 to 1 or higher is needed.

To obtain the largest number of nuggets per inch that will yield leak-tight joints at a given welding speed, the heat time should be adjusted to produce the required nugget properties, and the cool time should be short enough to provide the required nugget overlap. The reductions in nugget penetration and nugget overlap that occur with increasing cool time in resistance seam welding of 0.078-in.-thick 1010 steel are shown in Fig. 9.

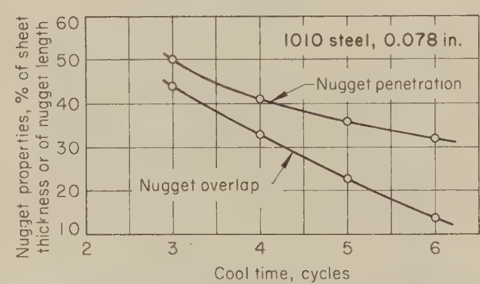
Effect of Welding Speed

The speed at which low-carbon steel can be seam welded depends on the desired weld quality and on the



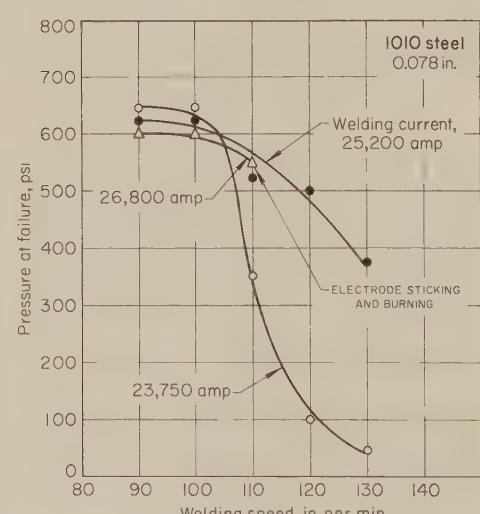
Welding conditions: heat time, 6 cycles; cool time, 5 cycles; welding speed, 55 in. per minute. (Source: Same as Fig. 6)

Fig. 8. Effects of welding current and electrode force on nugget width in seam welding 0.078-in.-thick 1010 steel



Welding conditions: heat time, 6 cycles; electrode force, 1500 lb; welding current, 18,950 amp; and welding speed, 55 in. per minute. (Source: Same as Fig. 6)

Fig. 9. Effects of cool time on nugget penetration and nugget overlap in seam welding 0.078-in.-thick 1010 steel



Welding conditions: heat time, 2 cycles; cool time, 1 cycle; electrode force, 1500 lb. Pillow-type samples were seam welded, at three welding-current values, then were inflated with air until failure occurred. (Source: Same as Fig. 6)

Fig. 10. Effect of welding speed on joint strength in seam welding 0.078-in.-thick 1010 steel at three levels of current

design, thickness and surface condition of the workpieces. The use of excessive welding speed causes a rapid reduction in weld strength, even with higher welding currents. As welding speed is increased, the welding current must be increased in order to develop sufficient heat in the work metal. Increased welding current causes surface burning of the work metal and electrode pickup, and thus, even with flood cooling, welding speed is limited.

The effect of welding speed on joint strength in welding 0.078-in.-thick 1010 steel at three different levels of welding current is shown in Fig. 10. Heat time was 2 cycles, cool time was 1 cycle and electrode force was 1500 lb. The values were obtained in pillow tests (see AWS C1.1-66, Section V) in which pillow-type specimens were seam welded at the three levels of current and then were inflated with air until rupture or leakage occurred.

Effect of Workpiece Design on Electrode Shape

Design of workpieces can affect the shape of the electrode face and the contour of the electrode wheel. A small-width seam can be made in a narrow flange by reducing the thickness of the wheel at the circumference, as in Example 429 in the article on Resistance Welding of Copper Alloys. To weld the dish-shape front of a clothes drier in Example 384 in the present article required the electrode wheel to be set at an angle, which in turn necessitated the face of the electrode to be machined at an angle to the side of the wheel (see Fig. 12). Sheets having stiffeners that cross the path of a seam weld require electrodes with notches, as shown in Fig. 3, if the welds are to be made without lifting the electrode from the sheet. Starting a seam weld close to the flange or sidewall of components that cross the path of a seam weld can be done by using segments of an electrode wheel, as was done in the example that follows.

Example 383. Use of a Segmented Electrode Wheel To Seam Weld Close to the Flange of a Stiffener (Fig. 11)

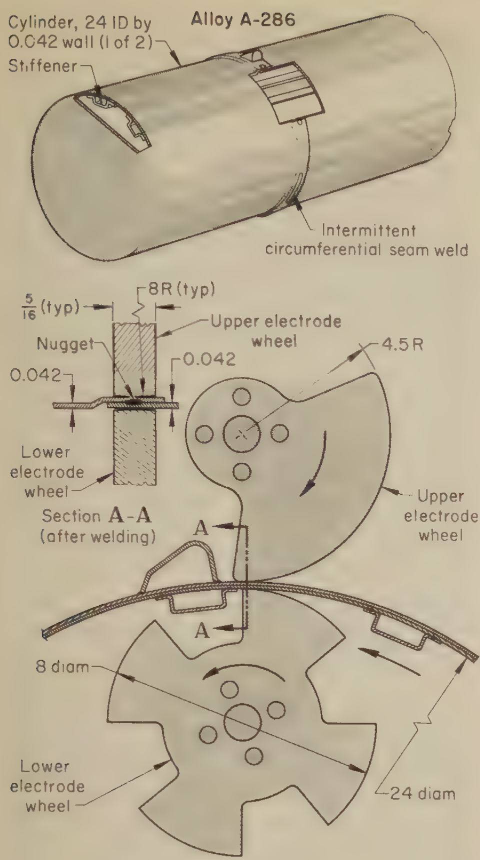
A cylindrical tank was made by resistance seam welding two sections of 0.042-in.-thick A-286 iron-base heat-resisting alloy. Components contained on both the inner and outer surfaces of the tank made it necessary to use segmented upper and lower electrode wheels to produce a leak-proof circumferential seam originating close to the flanges of the components. Both the upper and lower electrode wheels were shaped so that initial contact with the workpieces occurred at the edge of the segments (see Fig. 11).

Electrode motion was intermittent and the welding heat was supplied by three impulses from a three-phase alternating-current welding machine. A dual electrode force, consisting of a weld force and a forge force, was used to produce sound weld nuggets.

Equipment details and resistance seam welding conditions are given in the table that accompanies Fig. 11.

Width of Joint Overlap

The width of overlap at the joint (contacting overlap) must be sufficient to prevent collapse of the work metal at the edge adjacent to the seam. Table 3 lists recommended minimum widths of contacting overlap for resistance seam welding of low-carbon steel ranging in thickness from 0.010 to 0.125 in.



Setup for making intermittent circumferential seam weld

Equipment Details

Power supply	440 v, three phase
Welding machine	Semiautomatic, circular
Rating at 50% duty cycle	125 kva
Heat control	Phase shift
Upper electrode	5/16 in. wide by 9-in. diam; 8-in. face radius; segmented
Lower electrode	5/16 in. wide by 8-in. diam; 8-in. face radius; notched
Electrode material	RWMA class 3

Welding Conditions

Heat-control setting	70%
Heat time	5 cycles
Cool time	0.5 cycle
Heating impulses	3
Electrode force:	
Welding	1500 lb
Forging	2000 lb
Spot spacing	13 per inch
Welding speed	11 ipm

Fig. 11. Setup for resistance seam welding close to the flanges of stiffeners, using segmented electrode wheels (Example 383)

Excessive width of unwelded overlap between parts of seam welded assemblies can result in entrapment of dirt and moisture, which can present problems in subsequent manufacturing operations or in service. By use of the proper electrode force, welding current, heat and cool time, and electrode shape, the width of the weld nugget can be adjusted to minimize unwelded overlap, as in the following example.

Example 384. Automatic Circular Seam Welding in Which Unwelded Overlap Was Minimized To Avoid Moisture Traps (Fig. 12)

A drum for a clothes drier was made by resistance seam welding a 0.024-in.-thick wrapper to the flange of a round drum back 0.042 in. thick (Fig. 12a) and the flange of a round drum front 0.024 in. thick (Fig. 12b). All three components were of enameling iron (low-carbon steel). In each of the two circular seams to be welded, the total overlap was 7/16 in., as shown in Fig. 12. The three pieces were spot welded in position; then the wrapper was resistance seam welded to the drum back, and then to the drum front, producing two circular gastight seams.

In seam welding, it was important to ensure a minimum of unwelded overlap, and thereby to avoid moisture traps that could cause defects in a subsequently applied porcelain enamel coating. This was done (*a*) by adjusting the welding current, the heat-and-cool cycle, the welding speed and the electrode force so that a weld nugget was produced that was nearly as wide as the overlap of the flanges; and (*b*) by selection of electrode shape, dimensions and arrangement so that the full width of the drum-back flange (Fig. 12a) and nearly all of the width of the drum-front flange (Fig. 12b) were kept in contact with each lower electrode wheel.

The drum was welded in two automatic seam welding machines that differed only in rating. As shown in Fig. 12, both upper electrode wheels, and the lower wheel for the drum back, were mounted on horizontal axes; the axis of the lower electrode wheel for the drum front was mounted 18° from horizontal, to clear the dish-shape front.

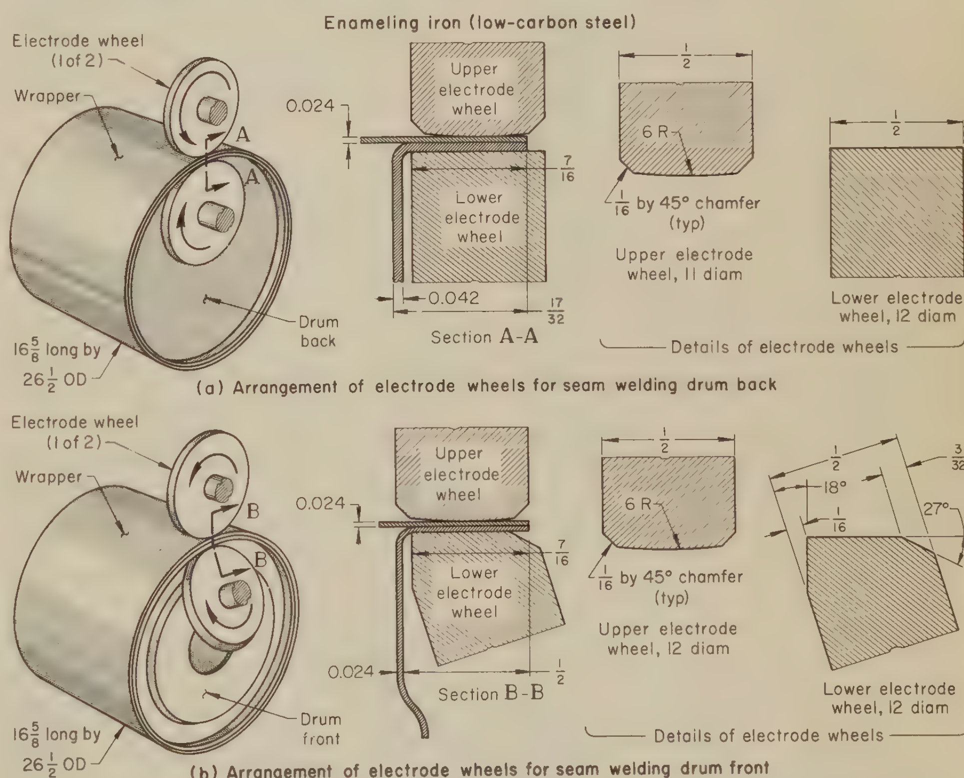
The face of each upper electrode wheel had a crown with a 6-in. radius, and had edges chamfered 1/16 in. by 45°. The faces of the lower electrode wheels were flat and were parallel to the work surface. This combination of electrode-face contours allowed the joint to be guided by a fixture on the welding machine, without attention from the operator once the weld had been started. The electrode material for both welds was RWMA class 2. The two lower electrode wheels and the upper wheel for the drum front were 12 in. in diameter. The diameter of the upper wheel for the drum back was 11 in.

In both welding machines, the upper electrode wheels were shaft driven through gears, and the lower wheels were idlers. The rotation of the powered upper wheels maintained a welding speed of 122 in. per minute. All shafts of the electrode wheels ran in tapered roller bearings. Brushes carried the welding current to the electrode wheels, and the bearings were insulated so that no current would pass through them. In each of the two welding operations, a timer stopped the machine after a preset interval, allowing only enough running time to complete the circular seam.

Re-dressing of the electrode wheels, in which about 1/16 in. of metal was removed, was done after welding about 1600 drums. Because of the reduction in wheel diameter resulting from each dressing of the electrode wheels, the speed of the gear-driven upper electrodes had to be adjusted to maintain the welding speed at 122 in. per minute. Additional equipment details and welding conditions are given in the table that accompanies Fig. 12.

Types of Seam Welds

Several types of resistance seam welds can be made, including lap seam welds joining flat sheets; flange-joint lap seam welds, in which at least one member has a flange that overlaps the mating piece; and mash seam welds, in which the work metal is compressed at the joint to reduce the joint thickness. Two other types of resistance seam



Equipment Details

Power supply	460 v, single phase
Welding machines (2)	Automatic, circular
Rating at 50% duty cycle	200 kva for welding drum back; 150 kva for welding drum front
Heat control	Phase shift
Electrode-ram operation	Air cylinder
Electrodes	Special design (see drawing)
Electrode material	RWMA class 2

Welding Conditions

Heat-control setting	80%
Heat time	3 cycles
Cool time	1 cycle
Electrode force:	
For welding drum back	1355 lb
For welding drum front	700 lb
Welding speed	122 ipm
Production rate	100 drums per hour

Fig. 12. Arrangement and design of electrode wheels used for minimizing unwelded overlap in seam welding a drum for a clothes drier (Example 384)

welds, made with the use of special techniques, are butt seam welds and foil butt seam welds.

In addition, both low-frequency and high-frequency induction and resistance welding are used for butt welding strip stock into tubes and other shapes.

Lap Seam Welds. The most common type of seam weld is a simple lap seam, in which the pieces to be welded are lapped sufficiently to prevent expulsion of weld metal. Applications include sealing of cans, water tanks and mufflers, in which watertight or gastight joints are needed.

In the following example, a drawn sump with flanges was seam welded to a cylindrical tub to make a watertight joint. The two components of the workpiece were designed to facilitate seam welding.

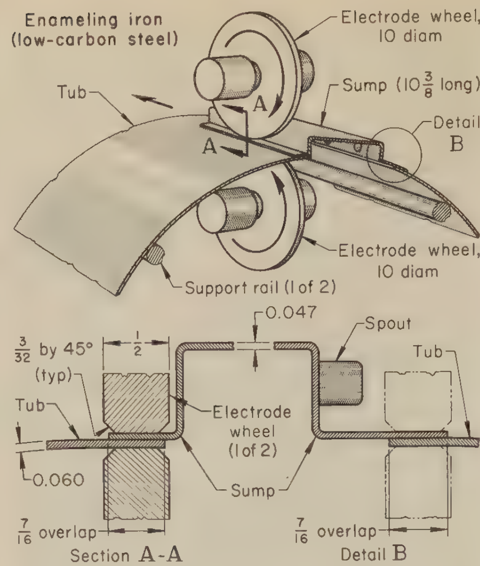
Example 385. Semiautomatic Straight Lap Seam Welding (Fig. 13)

The flanged sides of a drawn sump were lap seam welded to a cylindrical washer tub, as shown in Fig. 13, to make two straight watertight seams, 10⅜ in. long and parallel to the axis of the tub. Both components were of enameling iron (low-carbon steel); the sump was 0.047 in. thick, and the tub 0.060 in. thick.

To allow the upper electrode wheel to clear hose-connection spouts that were welded to one side of the sump, the flange on that side was made wider than the flange on the other side; the matching hole in the tub was made correspondingly large, to maintain a uniform overlap of 7⁄16 in. (see section A-A and detail B in Fig. 13). The nugget was made wide enough to avoid difficulties from unwelded overlap in subsequent porcelain enameling.

The welds were made in a semiautomatic longitudinal resistance seam welding machine that had two rails for supporting the tub, as shown in Fig. 13. The sump had previously been spot welded to the tub to hold the components in proper relation, and to simplify the resistance seam welding operation.

The workpieces were moved by the force and rotation of two knurl-driven electrode wheels, and were guided by the operator. The knurl drive continuously dressed the electrode wheels, which had double-bevel flat faces. The electrode faces were redressed after welding about 1600 tubs. Additional equipment details and welding conditions are given in the table that accompanies Fig. 13.



Equipment Details

Power supply	460 v, single phase
Welding machine	Semiautomatic, longitudinal
Rating at 50% duty cycle	200 kva
Heat control	Phase shift
Electrode-ram operation	Air cylinder
Electrode material	RWMA class 2

Welding Conditions

Heat-control setting	90%
Heat time	4 cycles
Cool time	4 cycles
Electrode force	1025 lb
Welding speed	65 ipm
Electrodes	½ in. wide by 10-in. diam; double bevel; 5⁄16-in.-wide flat face
Production rate	60 tubs per hour

Fig. 13. Setup for resistance lap seam welding of a flanged sump to a washer tub (Example 385)

Flange-joint lap seam welds are used in joining assemblies having one straight member and one outward-flanged member at the joint to be welded, such as the duct shown in Fig. 14(a), or assemblies with two outward-flanged members, such as automotive gasoline tanks, as shown in Fig. 14(b). Common applications include containers with outturned bottoms or tops, and ducts or structural parts with outturned sides. Unless the workpiece length is less than the usable throat depth of a longitudinal machine, seam welds of this type are made on a circular machine.

Often the container ends, such as the drum front in Example 384 (Fig. 12), are dished for added strength, and one or both electrode wheels must be mounted at an angle to clear the workpiece. Wheel-diameter limitations may also necessitate setting a wheel at an angle, as in the view at right in Fig. 14(a).

Flange-joint seam welds can also be used for welding assemblies in which the flanges face inward at the joint (see Fig. 14c); however, to reduce overhang of the arm supporting the lower electrode, or the required throat depth of the machine, the length of the workpiece should be kept to a minimum. If the lower-electrode support is small, too much overhang can result in excessive deflection of the support, and thus cause inconsistent weld quality and unacceptable welds due to reduced electrode pressure.

In the following example, three thicknesses of metal were welded together in a gastight flange joint. A resistance seam weld nugget prevented the piece of metal at the center of the joint from melting faster than the two outer pieces in gas tungsten-arc seal welding the edges of the workpiece.

Example 386. Use of Resistance Seam Welding and Gas Tungsten-Arc Welding To Produce a Gastight Joint (Fig. 15)

A 10-in.-ID bellows assembly for a fuel duct for a rocket motor, shown in Fig. 15, consisted of a straight section of a 0.020-in.-thick bellows wall sandwiched between two 0.040-in.-thick rings, all made of nickel alloy 718. Originally, the joint was made by edge-flange welding using the gas tungsten-arc process. When the joint was tested hydrostatically under an internal pressure of 160 psi, the joint did not leak; but when it was tested with a helium mass spectrometer under an internal vacuum, significant leakage was detected.

An investigation revealed that during gas tungsten-arc welding, the bellows wall melted back faster than the rings, so that weld metal was deposited at the edges of the rings only — which provided a leak path around the unwelded edge of the bellows. (See detail A, original method, in Fig. 6 for Example 276, on page 284.)

The problem was solved by first resistance seam welding the three workpieces together (see operation 1 in Fig. 15), then machining the edges back to the edge of the seam weld. A gas tungsten-arc weld was then deposited as before to ensure a gastight joint (see operation 2 in Fig. 15). The completed seam and arc welded joint was gastight under test conditions.

Before welding, the workpieces were cleaned by immersing them for 15 minutes in a solution of 30 to 40% nitric acid and 2 to 5% hydrofluoric acid that was at room temperature. The inner and outer rings were completely immersed; the bellows was immersed only to the first convolution.

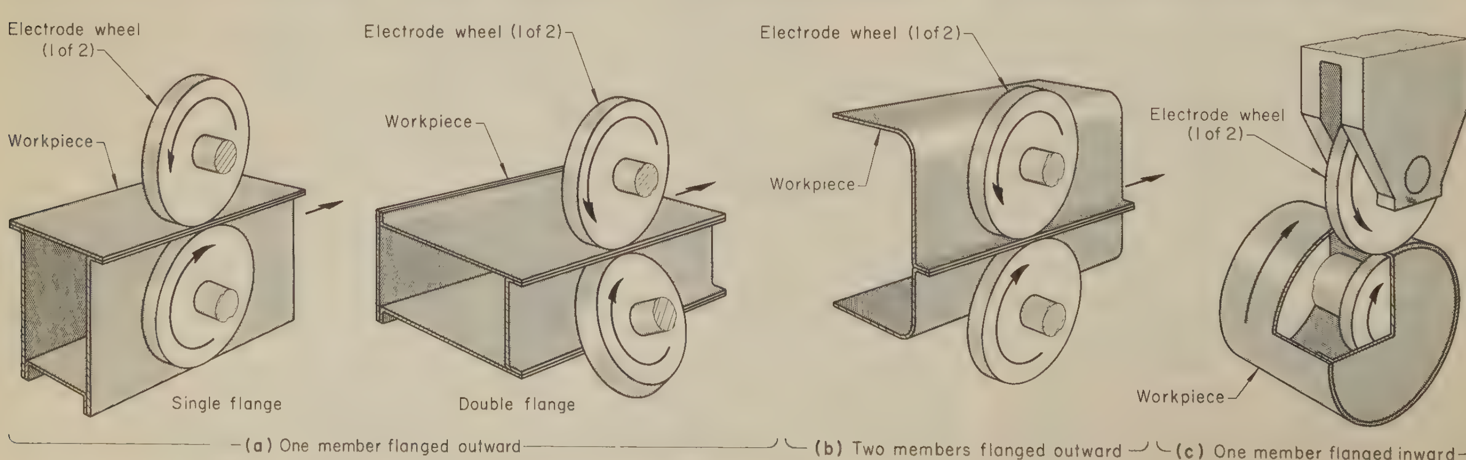


Fig. 14. Typical arrangements of electrode wheels for making various types of flange-joint lap seam welds

Equipment details and welding conditions for resistance seam welding are given in the table that accompanies Fig. 15. Conditions for gas tungsten-arc welding are given in Example 276, in the article on Arc Welding of Heat-Resisting Alloys.

Mash seam welds are produced by overlapping two sheets by an amount ranging from 1 to 1½ times the sheet thickness and applying a high electrode force and a high continuous welding current. The resulting weld thickness is 10 to 25% greater than the sheet thickness. Flat electrodes are used that are wide enough to control the weld thickness. The electrode force, welding current, welding speed, weld thickness and amount of overlap are all interrelated and must be accurately controlled to ensure consistent results. Mash seam welds require higher electrode force, welding current and welding speeds than are used in conventional seam welding.

The sheet overlap determines the amount of metal to be redistributed, and thus affects weld thickness. Therefore, the workpieces must be rigidly and accurately clamped or tack welded to prevent lateral motion during the welding operation. In applications where the mashed surface must be as flat as possible to facilitate porcelain enameling and to present a good appearance, a bar-type electrode is used against the surface to be enameled, and an electrode wheel is used against the other surface. When the finished appearance is important, the weld can be ground or roll planished to remove surface defects.

The most satisfactory mash seam welds are made in low-carbon steel. The maximum stock thickness that can be successfully mash seam welded is about 0.060 in. Stainless steel has been mash seam welded in some applications. Because of their narrow plastic range, nonferrous metals generally cannot be mash seam welded. This process is widely used in the manufacture of refrigerator cabinets, stoves, laundry equipment and other products that receive porcelain enamel coatings.

Butt seam welds are made by a special resistance seam welding technique in which the two abutting edges are heated and lightly forged together. There is a slight depression where the electrode wheels compress the plastic metal. This type of weld usually has low strength.

High-quality butt seam welds can be made in tubing by resistance heating the edges of roll-formed strip stock and forging them together with squeeze rolls. The welded tube has a small upset area on each side of the joint, which is continuously removed by scarfing tools.

This technique differs from upset butt welding in that the entire joint is not forged together simultaneously, but rather is forged together progressively as the electrode wheels traverse the seam.

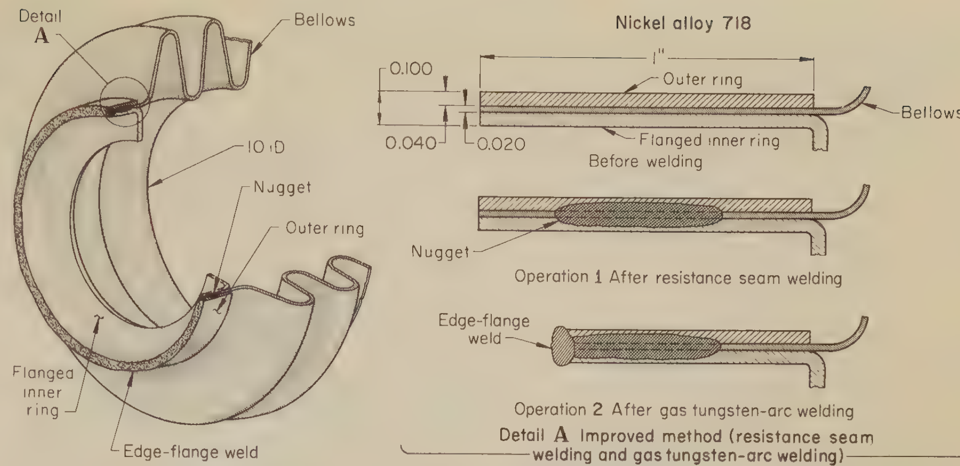
Foil Butt Seam Welds. The strength of a butt seam weld can be increased by adding metal to the surfaces perpendicular and adjacent to the abutting edges of the joint. This technique is called foil butt seam welding. A thin, narrow strip of metal, usually 0.010 in. thick and ⅛ to 5⁄32 in. wide, is introduced on one or both surfaces adjacent to the joint as the workpiece is passed between conventional seam welding electrodes. This technique produces a smooth, nonoverlapping seam that is high in strength and neat in appearance. Highest-quality foil butt seam welds show nugget penetration to the foil-workpiece interface, complete foil bonding, and smooth, regular surface contours. The only edge preparation required is to ensure that the sheared edges are clean and straight without excessive burr or gap when they are butted together.

The thin strip or foil acts as a bridge to distribute the welding current evenly to both sheets, concentrates the current in the joint, helps contain the molten nugget as it grows and then cools, and provides metal for a slightly raised bead.

The variables having the greatest effect on the tensile strength of foil butt seam welds are welding current, welding speed, size of the gap between the edges of the butted workpieces, and thickness of the work metal. For the commonly used thicknesses of low-carbon steel, welding speeds similar to those used in conventional seam welding are permissible, provided that the gap is no wider than 0.015 in. Interrupted current and partial-wave continuous current both are used for foil butt seam welding.

Foil butt seam welded assemblies are ordinarily used in the as-welded condition. In those applications requiring at least one side of the weld to be finished flush to provide a smooth, blemish-free surface, removing some of the foil reduces the strength or reinforcement that the foil may have contributed to the weld.

In the following example, foil butt seam welding was used to make a smooth joint in a furniture component.



Equipment Details and Welding Conditions

Power supply ....440 v, three phase	Squeeze time ....0.3 cycle
Welding machine ....Circular	Preheat time ....4 impulses of 2 cycles each
Rating at 50% duty cycle ....250 kva	Weld time ....5 impulses of 4 cycles each
Rating of secondary circuit ....130,000 amp	Postheat time ......4 impulses of 4 cycles each
Heat control ....Phase shift	Forge time ....5 cycles
Electrodes ....RWMA class 3, 10-in. diam, ½ in. wide, reduced to 3⁄16 in. wide at face; 3-in.-radius face	Cool time ....0.5 cycle
	Electrode force, welding ....800 lb
	Electrode force, forging ....800 lb
Preheat-current setting ....0.6% (780 amp)	Motor speed ....24 ipm
Welding-current setting ......11% (14,300 amp)	Spot spacing ....12 spots per inch
Postheat-current setting ......0.8% (1040 amp)	Time for resistance seam welding ......1.25 min

Fig. 15. Bellows assembly for a rocket-motor fuel duct that was made leakproof under vacuum by resistance seam welding and gas tungsten-arc welding (Example 386)

Example 387. Foil Butt Seam Welding a Table Leg To Avoid a Finishing Operation (Fig. 16)

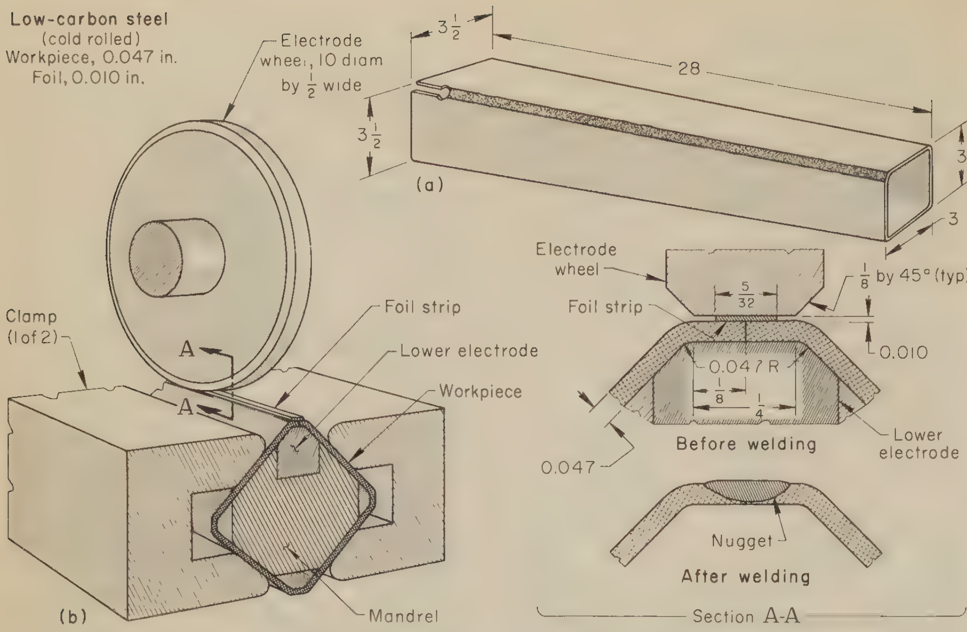
Figure 16(a) shows a tapered table leg that was foil butt seam welded from 0.047-in.-thick low-carbon steel. If welded by other methods, this leg would have required a finishing operation before being painted, which would have added to the total cost. Foil butt seam welding slightly increased the thickness of the welded joint, but the edges of the foil blended into the base metal and made a smooth seam (see section A-A in Fig. 16).

The leg was welded in a 300-kva automatic longitudinal resistance seam welding machine that had an electrode wheel mounted on a movable carriage. An air-operated ram raised and lowered the electrode wheel, and forced it against the workpiece during welding. The lower electrode was a bar electrode mounted in a mandrel that was fastened to the stationary frame. The mandrel and electrode conformed to the shape of the leg, as shown in Fig. 16(b).

In operation, the table leg was placed over the mandrel and clamped in place, with the edges of the joint tightly butted. The electrode wheel was automatically moved into position above the workpiece, low-carbon steel foil (0.010 in. thick by 5⁄32 in. wide) was automatically fed over the joint, the wheel was lowered and welding force was applied. As the welding current passed from the upper electrode wheel through the foil and the abutting edges of the table leg to the lower electrode, the carriage advanced the wheel along the seam to produce a resistance welded joint. Because foil was used on one side only, weld penetration was 80 to 90% of stock thickness.

The welding speed was 20 ft per minute. Production rate was 220 table legs per hour. The electrodes were made of RWMA class 2 material. The upper electrode was continuously cleaned using a scraper-type wheel dresser. The scraper needed resharpening after each four to five hours of operation. The electrode force was 1200 lb.

For 1000 legs, the cost of foil was $6.36, and allowance for wear of the electrode wheel was $1.60. Additional details with regard to the equipment and welding conditions are given in the table that accompanies Fig. 16.



Equipment Details and Welding Conditions

Power supply ....440 v, single phase	Upper electrode ......½ in. wide by 10-in. diam; double bevel; ¼-in.-wide flat face
Welding machine .....Automatic, longitudinal, with movable carriage for upper electrode	Lower electrode ....28-in.-long bar; double bevel; ¼-in.-wide flat face (see drawing)
Rating at 50% duty cycle ....300 kva	Electrode material ....RWMA class 2
Heat control ....Phase shift	Welding current ....Continuous
Electrode-ram operation ....Air cylinder	Welding speed ....20 fpm
Electrode force, max ....1200 lb	Production rate ....220 legs per hour

Fig. 16. Setup for foil butt seam welding a table leg made of low-carbon steel (Example 387)

Seam Welding of Coated Steel

Resistance seam welding of low-carbon steel that has a thin coating of zinc, aluminum or terneplate can be done satisfactorily by proper selection of welding conditions. The metal coating increases the contact resistance, and thus welding of coated steel requires higher welding current and electrode force than are needed for welding similar thicknesses of uncoated steel. The welding speed must be limited to avoid excessive heating of the electrode and arcing at the workpiece interface, and immersion or flood cooling is recommended to permit a higher welding speed to be used, as well as to improve electrode life. In addition, a jet of water can be directed onto the work at the point where the work leaves the electrode wheels.

The RWMA class 2 copper alloy materials are best for electrodes used in seam welding of coated steel. Electrode life is shorter than in welding uncoated steel because of electrode pickup and higher welding currents. Because electrode pickup is considerable, the welding machine should be equipped with a knurl drive to break up and remove the pickup and to maintain the face width of the electrode. A scraper blade may be needed also for proper electrode maintenance.

For additional information, the reader is referred to the sections that discuss resistance spot welding of steel with various types of coatings, on pages 420 to 422 in this volume.

Other Examples of Resistance Seam Welding

Table 4 lists examples of resistance seam welding presented elsewhere in this volume. These deal with application of the process to stainless steel, aluminum alloys, and copper alloys.

Table 4. Examples of Resistance Seam Welding Presented Elsewhere in This Volume

Examples 410, 411, 412: Welding 3 combinations of different-thickness 316 and 321 stainless
Example 413: Control of current and electrode pressure for no-distortion welding of 0.002-in.-thick type 304 stainless diaphragms
Example 414: Effect of electrode-wheel design and maintenance in welding 17-7 PH stainless steel
Example 415: Seam welding vs silver brazing for sensitive tube-to-plug joint between types 430F and 321 stainless steel
Example 429: Welding of two 0.0045-in.-thick diaphragms made of a copper-nickel-manganese alloy (60 Cu, 20 Ni, 20 Mn)
(Unnumbered; see page 473): Welding of aluminum alloys 6061-T6 and 2014-T6

Projection Welding

*By the ASM Committee on Resistance Welding of Steel**

PROJECTION WELDING is a resistance welding process in which current flow and heating are localized at a point or points predetermined by the design or configuration of one or both of two parts to be welded. The process is closely related to resistance spot welding, in which current flow and heating are localized by one or both electrode contact faces, which determine the location, size and shape of the weld produced.

This article is concerned primarily with projection welding of low-carbon and low-alloy steels, although much of the information presented is applicable also to other work metals. Projection welding of stainless steel, aluminum alloys and copper alloys is described in the next three articles in this volume.

In the usual application of projection welding, a projection, specially designed and formed on one of two conforming workpieces, is used to concentrate current flow and heating at the point where the weld is to be made.

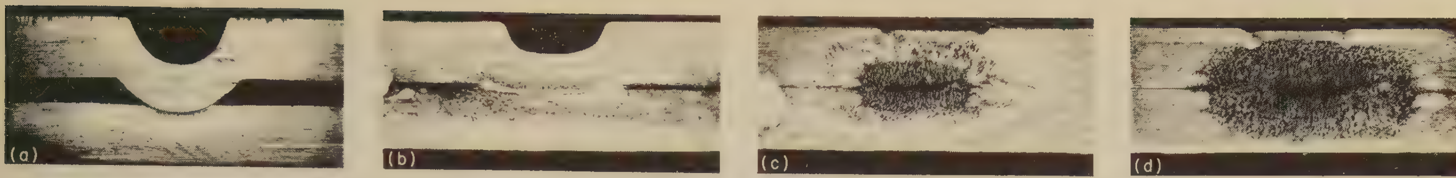
Projections may be of any practical shape that can properly concentrate the welding current. In cross-wire projection welding, the curved surfaces of two intersecting wires perform the function of a projection. The shapes of parts also take the place of conventional projections in projection welding other special types of joints.

Electrodes or welding dies are used to conduct current to the workpieces, and to apply the welding force. Force is always applied before, during and after the application of current to ensure a continuous electrical circuit and to forge the heated workpieces together. Welding dies may also hold and clamp the workpieces in proper relation to each other before and during the welding operation.

Formation of Weld. The formation of a projection weld nugget, which depends on the design of the projection, the selection of welding conditions, and the adequacy of the resistance welding equipment, is shown in stages in Fig. 1, which is based on projection welding of 0.092-in.-thick low-carbon steel using embossed spherical projections and a weld time of 20 cycles (⅓ second).

At first, as shown in Fig. 1(a), the workpieces are brought together under pressure without application of welding current, and the projection may be slightly compressed and indented into the surface of the mating workpiece. Figures 1(b), (c) and (d) show the stages of formation of a typical weld at 20%, 60 to 70%, and 100% of the weld time (or "heat time").

*For committee list, see page 401. Most of the examples in this article were contributed by members of other Metals Handbook welding committees. Additional examples on projection welding that appear in other articles in this volume are listed in Table 8, page 455.



(a) Components are brought together between electrodes, without application of current. Projection on upper component is pressed against lower component by electrode force. (b) At 20% of weld time (or "heat time"), collapse of projection is nearly complete, and a pressure weld is formed. (c) At 60 to 70% of weld time, fused weld nugget has developed about half its final thickness and diameter, sheet separation is zero, and upper surface is flat against the upper electrode. (d) At end of weld time, nugget has reached full thickness (penetration) and diameter. (Adapted from: J. F. Harris and J. J. Riley, "Projection Welding Low-Carbon Steel Using Embossed Projections", *Welding Journal*, Apr 1961)

Fig. 1. Four stages in the development of a weld nugget in 0.092-in.-thick low-carbon steel during projection welding, using embossed spherical projections 0.050 in. high and a weld time of 20 cycles

At about 20% of weld time (Fig. 1b), collapse of the projection is nearly complete, and a pressure weld is formed. A nugget of fused weld metal does not begin to form until about 50% of the weld time has elapsed.

At about 60 to 70% of weld time, as shown in Fig. 1(c), fusion has progressed a sufficient distance from the interface to produce a well-defined weld nugget that has about half its final thickness (penetration) and diameter. Sheet separation adjacent to the weld nugget has been reduced to zero, and the softened metal above the nugget has been flattened against the face of the upper electrode (compare with Fig. 1b). Nugget diameter, penetration and shear strength continue to increase as weld time progresses. Figure 1(d) shows the fully developed weld nugget.

Applicability of Process

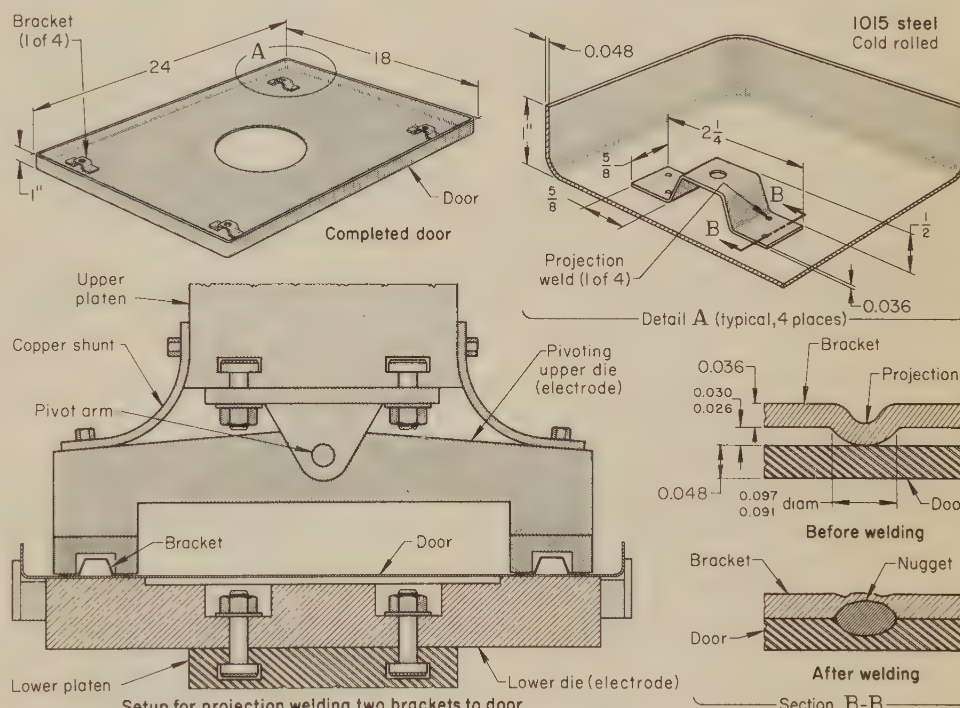
The principal application of projection welding is the joining of stamped low-carbon and low-alloy steel parts (punched, drawn or formed) on one of which a projection has been formed during the stamping operation. Projection welding is also used for joining screw-machine parts to stamped parts; the projection is machined or coined on the end of the screw-machine part. Fasteners or mounting devices, such as nuts, screws, brackets, pins, bosses, handles and clips, can be attached to various products by projection welding. This technique is of special value in mounting attachments to surfaces of which the back side is inaccessible to a welding operator, and in applications where the mounting surface must be leakproof at the weld joint.

Projection welding is most successful in workpieces 0.022 to 0.135 in. thick. Stock 0.010 in. thick has been projection welded; however, projection design is critical and machines with low-inertia heads and fast follow-up are needed. Sections less than 0.010 in. thick are more adaptable to spot welding.

Projection welding of crossed wires is used for making such diverse items as stove and refrigerator racks, soap dishes, lampshade frames, gratings, grills, and electrical connector networks for electronic applications.

Advantages. The principal advantages of projection welding are:

1. The number of welds that can be made simultaneously with one operation of the welding machine is limited only by the ability of the controls to regulate current and force.
2. Because of greater current concentration at the weld, and thus less chance of shunting, narrower flanges can be welded, and welds can be spaced closer together, by projection welding than by spot welding.
3. Electrodes used in projection welding have faces larger than the projection or pattern of projections, and larger than faces of electrodes used for making spot welds of comparable nugget diameter, and thus, because of lower current density, require less maintenance than do spot welding electrodes.
4. Tooling construction for projection welding usually combines welding dies, or electrodes and electrode holders, with workpiece locators in one assembly, which frequently can be designed for welding two or more small workpieces to one larger one.
5. Projection welds can be made in metal that is too thick to be joined by resistance spot welding.
6. Flexibility in the selection of projection size and location allows welding of workpieces in thickness ratios of 6 (or more) to 1. Workpieces in thickness ratios greater than about 3 to 1 sometimes are difficult to spot weld.
7. Weldments requiring a minimum of surface marking on one side can be produced by embossing projections on the component with less-critical appearance requirements. The slight bump raised in welding (if objectionable) can be removed in a simple mechanical finishing operation.
8. Projection welds can be located more accurately, and are more consistent in



Comparison of Costs for Spot Welding vs Projection Welding

Item	Spot welding	Projection welding
Production rate, doors per hour	75	210
Welding cost per 100 doors	$5.60	$2.01
Finishing cost per 100 doors	$3.92	$3.16
Total cost per 100 doors (labor plus overhead)	$9.52	$5.17
Saving per 100 doors		$4.35
Annual saving (750,000 doors produced per year)		$32,625.00

Equipment Details for Projection Welding

Welding machine	Press type, RWMA No. 2
Rating at 50% duty cycle	100 kva
Current, max	46,000 amp
Electrode material	RWMA class 2
Electrode force, max	1800 lb

Conditions for Projection Welding

Welding current	32,000 amp
Heat-control setting	90%
Electrode force	1200 lb
Squeeze and hold times	10 cycles each
Weld time	6 cycles

Projection welding replaced spot welding, in which the 16 welds (four per bracket) had to be made one at a time because of close spacing. As shown in the table, the change of process resulted in a 180% increase in production rate and a 46% saving in costs.

Fig. 2. Setup for joining four brackets, two at a time, to a clothes-drier door (Example 388)

diameter and thickness (penetration), than spot welds (and thus, for a given strength, can be smaller in average size than spot welds).
9 Oil, rust, scale, plating and other work-metal coatings interfere less with projection welding than with spot welding.

In spite of the additional cost of embossing or otherwise providing projections, projection welding often is more economical than spot welding. A greater number of welds can be made simultaneously, surface finish can be better preserved, and handling sometimes can be reduced, as in the application described in the example that follows.

Example 388. Change From Resistance Spot Welding to Projection Welding That Increased Production and Reduced Costs (Fig. 2)

Originally, spot welding was used for attaching four brackets to the low-carbon steel door of a clothes drier (Fig. 2, upper left). The 16 spot welds (four per bracket) were made one at a time.

Production rate was increased by 180% and costs were reduced by 46% when spot welding was replaced by projection welding for attaching the brackets. With the setup shown at lower left in Fig. 2, projection welds were made eight at a time, attaching two brackets to the door simultaneously, and loading of parts into the welding machine was faster than with the fixture used for spot welding.

The upper die (electrode) was pivoted to equalize the welding force on each of the brackets. A means was provided in the upper die for locating and holding the brackets for welding, and the lower die incorporated gages for positioning the door.

Surface finishing was done in less time after projection welding than after spot welding. Equipment details and conditions for projection welding, along with a comparison of production rates and costs for the original and improved methods, are given in the table that accompanies Fig. 2. Yearly production was 750,000 doors.

In the following example, projection welding was selected over arc welding or resistance spot welding for greater productivity at lower cost (including the cost of electrode maintenance).

Example 389. Projection Welding of Mounting Brackets to a Panel (Fig. 3)

Four press formed right-angle mounting brackets, 2 in. long and 0.156 in. thick, were projection welded to a panel 0.090 in. thick, as shown in Fig. 3. The brackets and the panel were made of 1010 steel. Each bracket, on which three spherical projections, 0.056 in. high by 0.250 in. in diameter, had been produced during press forming, was welded in one operation in a press-type projection welding machine. Equipment details and welding conditions are given in the table with Fig. 3.

The three-weld joint in each bracket was required to withstand a shear load of 2000 lb, and when peel tested, was considered sound if buttons of metal were pulled from the panel.

The electrode faces were flat and were longer than the brackets, as shown at lower right in Fig. 3. The lower electrode had to be dressed after 60 to 80 hours of welding, and the upper electrode, after 30 to 40 hours.

The welding machine and controls cost $6300. The yearly cost for maintenance of electrodes (labor at $4.08 per hour) and for purchase of replacement electrodes was $185. Annual production was 20,000 panels.

Projection welding was selected because it could provide greater productivity, at lower cost, than could arc welding or resistance spot welding. Production rate was 100 panels per hour for projection welding, compared to estimates of 15 per hour for arc welding and 50 per hour for spot welding. Cost per panel was $0.08 for projection welding, compared to estimates of $0.50 for arc welding and $0.16 for spot welding. Cost of electrode maintenance was lower for projection than for spot welding.

Because of its speed and adaptability to automatic control, projection welding is readily integrated with high-speed forming, trimming and other press operations in automatic multiple-station machines, as in the welding of electrical contacts described in the following example.

Example 390. Projection Welding Combined With Cutoff, Coining and Trimming in an Eight-Station Automatic Machine (Fig. 4)

The mercury-switch contact assembly shown in Fig. 4, which consisted of a platinum-nickel wire, 0.0038 in. thick by 0.0105 in. wide, and a nickel-iron pole piece, originally was projection welded manually in a separate operation. To increase production and reduce costs, projection welding was done automatically and was combined with cutoff, coining and trimming in an eight-station automatic machine. After welding, the wire was coined to form three contact surfaces 0.004 in. wide by 0.006 in. high by 0.010 in. long, as shown in Fig. 4.

Details of Improved Method. The assembly was made at the rate of 800 pieces per hour. The operations were performed on a cam-operated eight-station rotary-indexing table as follows:

1 Manually load pole piece into the lower die (the lower welding electrode, which also served as a support during coining and trimming).
2 Automatically align pole piece and apply a drop of alcohol for cleaning and to provide cooling during welding.
3 Feed and cut off platinum-nickel wire, and projection weld to pole piece (Fig. 4, section B-B).
4 Idle.
5 Coin three contacts on wire, and partly trim excess wire (Fig. 4, section C-C).
6 Remove excess wire (Fig. 4, section C-C).
7 Eject finished weldment.
8 Idle.

Prior to assembly, the nickel-iron pole piece was degassed in a hydrogen atmosphere. In station 3, after the pole piece was located in the lower die, the upper die was lowered to within 0.002 in. of the welding position. The rectangular-section wire was fed from a spool and was guided across the pole piece by a slot in the upper die. The wire was cut off and the upper die was lowered to make the weld.

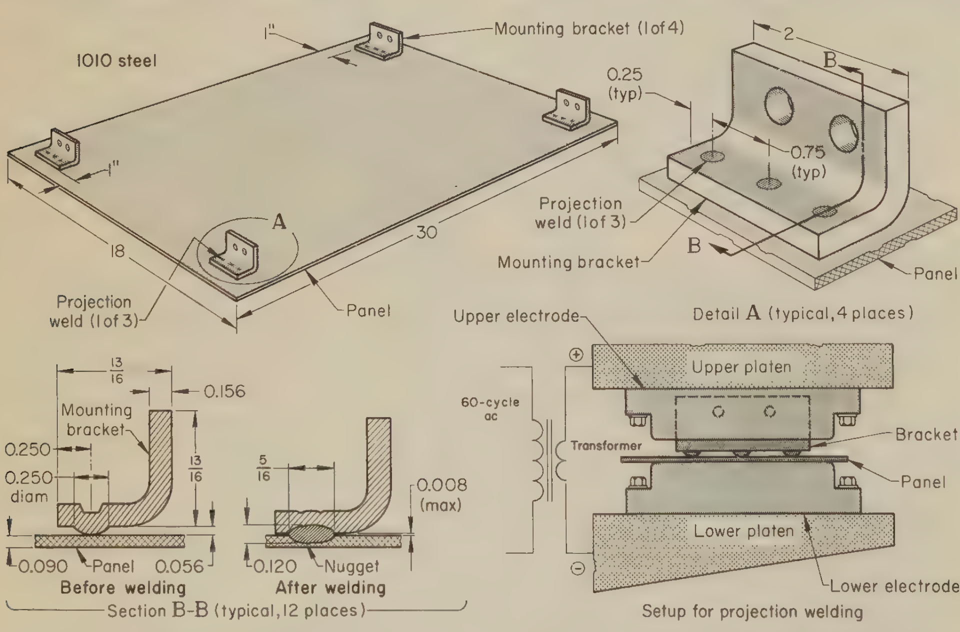
Comparison With Original Method. Previously, the same basic operations had been performed manually. The improved (automatic) process required greater care in aligning the workpieces and the dies. The machine cost $15,950, but production per man-hour was more than quadrupled over the original method, as shown in the table with Fig. 4, and there were fewer rejections. The resulting decrease in production costs allowed amortization of the cost of the machine in 147 working days, or after welding of 938,000 assemblies.

Quality Control. Five assemblies were inspected every 15 minutes. First they were dimensionally inspected in an optical comparator at a magnification of 50 diameters. Then they were tested destructively by applying force to the faces of the three coined contacts. The weld was required to hold until the contacts had been bent 90°.

Conditions for projection welding by the improved method, and a comparison of labor costs for cutoff, coining, welding and trimming by the original and improved methods, are given in the table with Fig. 4.

Limitations of projection welding include the following:

1 Forming of one or more projections on one of the workpieces may require extra operations.
2 When several welds are made at once with the same electrode, alignment of the work and dimensions (particularly height) of the projections must be held to close tolerances to obtain consistent weld quality.
3 In any one operation, welding is limited to joining two thicknesses of metal and, as in spot welding, the



Equipment Details	
Welding machine	Press type
Rating at 50% duty cycle	300 kva
Current, max	80,000 amp
Electrode material	RWMA class 3 (special shapes and sizes)
Controls	Synchronous

Welding Conditions	
Welding current and voltage	31,000 amp, 12 v
Electrode force	2400 lb
Squeeze time	60 cycles
Weld time	26 cycles (single pulse)
Hold time	40 cycles
Production per hour	100 assemblies

Fig. 3. Projection welding of four mounting brackets to a panel. Projection welding was selected over arc or resistance spot welding to maximize production rate. (Example 389)

shape of the work and location of the projections must be compatible with application of the electrode force.

4 Nugget size is limited by the size of the projection.

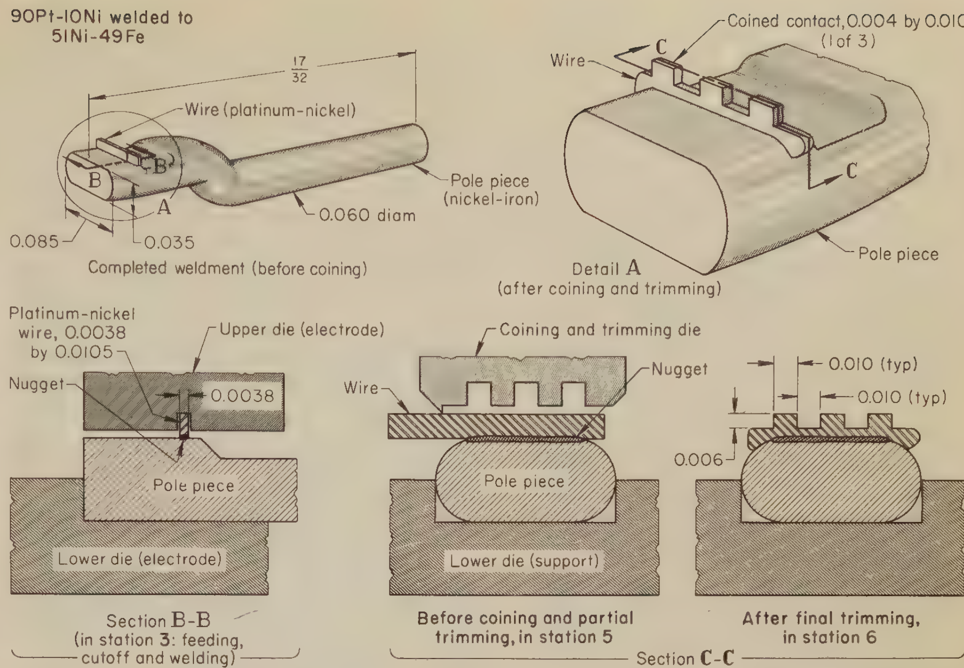
Welding Machines

Press-type machines, with either single-phase or three-phase transformers, are used for projection welding. The welding head in these machines is guided by bearings or ways and moves in a straight line. Platens with T-slots or tapped holes are used for mounting the welding dies or electrodes. Rocker-arm machines generally are not used for projection welding because the electrode moves in an arc that can cause slippage between the components as the projection collapses.

The welding head can be hydraulic, spring, magnetic or air actuated. Many machines have a low-inertia welding head, or a means of uncoupling the electrode holder, to provide fast follow-up as the projection collapses. A schematic arrangement of a low-inertia welding head is shown in Fig. 5.

At the start of the welding stroke (Fig. 5a), equal air pressure is applied to the top of the piston and to the diaphragm. By the time the piston has completed its travel, the diaphragm has been compressed by the retraction of the internal shaft. Retraction of the internal shaft simultaneously compresses the diaphragm and closes the welding-current switch; control lever for the switch rides in the shaft collar.

At the instant the welding current is initiated (Fig. 5b), the only remaining mass to be moved is the internal shaft and its attached electrode. Air pressure acting on the diaphragm and the force of the compressed spring between the inner and outer shaft easily overcome the low inertia of the system and move the upper electrode downward as the projection collapses. Thus the workpieces are kept in close contact under partial electrode force until the welding head follows and forges the weld region with the full electrode force (Fig. 5c). A welding head like that shown in Fig. 5 was used in Example 393.



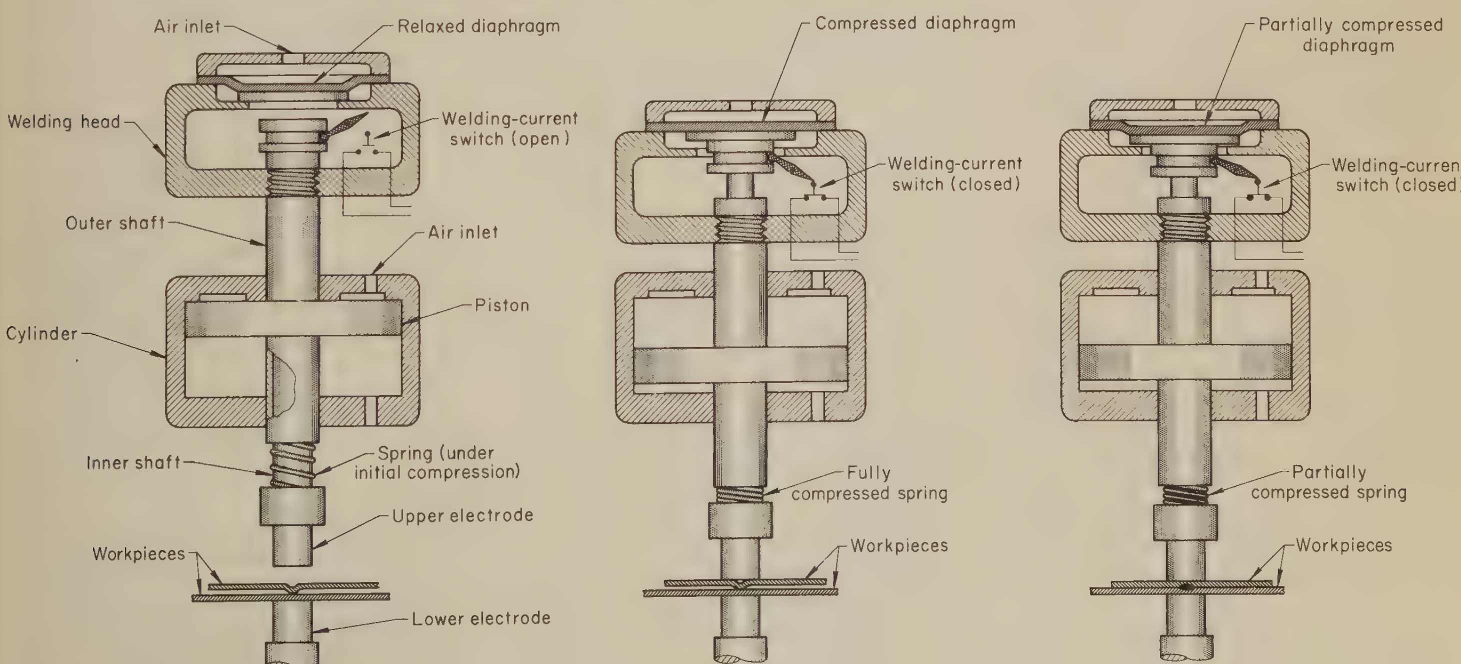
Item	Original method (manual)	Improved method (automatic)
Comparison of Labor Costs(a)		
Assemblies per man-hr	180	800
Number of operators	2	1
Cost per assembly at $4 per man-hr	$0.022	$0.005
Saving per assembly	...	$0.017

Conditions for Automatic Projection Welding

Transformer rating at 50% duty cycle ....5 kva
Electrode material ......RWMA class 10 (Cu-W)
Welding voltage ....1.5 v
Electrode force ....0.6 lb
Squeeze and hold times ....5 cycles each
Weld time ....2 cycles

(a) For cutoff, projection welding, coining and trimming

Fig. 4. Mercury-switch contact assembly for which projection welding was combined with cutoff, coining and trimming in an eight-station automatic machine (three stations shown), to increase production and reduce costs compared with original method (Example 390)



(a) Welding head in open position

(b) Welding head in position for squeezing and heating projection

(c) Welding head at instant of projection collapse and start of nugget formation

Air pressure on the diaphragm and the force of the compressed spring overcome the low inertia and move the upper electrode downward as the projection collapses, keeping the workpieces in contact. The welding head follows, to forge the weld region with the full electrode force.

Fig. 5. Low-inertia welding head for a projection welding machine

Welding-machine controls are usually of the synchronous type. Phase shift and pulsation timing are often included on single-phase or three-phase machines, to regulate welding current. Pulsation timing may be helpful when welding thick metal or unequal thicknesses, and to compensate partly for slow follow-up. On single-phase machines, slope control is sometimes used in special applications, generally for the same purposes as are served by pulsation timing.

For additional information on resistance welding machines and controls, see the article on Resistance Spot Welding, which begins on page 401.

Metals Welded

The metal that can be projection welded most satisfactorily is low-carbon steel (0.20% C max). Naval brass, Monel (nickel-copper) alloys and austenitic stainless steels have also been projection welded. Any two of these metals can be projection welded.

Coated metals, such as galvanized steel, terneplate, tin plate and aluminized steel, are successfully welded, but considerable electrode maintenance is usually needed. (See "Projection Welding of Coated Steel", page 450.)

Not all metals can be projection welded, because some are not strong enough to support projections; some brasses cannot be projection welded because the projections collapse too rapidly under pressure. Aluminum has been projection welded only to a limited extent, and best results are obtained with extruded parts, using conventional projections. Thin steel (less than 0.010 in. thick) usually is more easily spot welded than projection welded because of the difficulty of forming projections that will not collapse before reaching the welding temperature. Free-machining steel sometimes can be projection welded using specially designed joints and electrodes (see Example 396), but generally is difficult because sulfur and phosphorus segregation causes brittle welds.

Metallurgical Effects of Projection Welding

The rate of quenching projection welds is extremely rapid in thin members, because of the closeness of the water-cooled electrodes to the weld nugget. Although the total amount of heat is low because of the short weld times and the small amount of metal heated, severe solid-metal quenching is obtained. Under some conditions, quench rates for projection welds may be so severe that the fully hardened condition is achieved even in low-carbon steels. Therefore, recommended practice limits the carbon content of carbon steels to 0.20% max, unless special techniques are employed.

Cleaning of Workpieces

Optimum welds on all metals are obtained when surfaces are clean and without scale, oxide, excessive oil and grease, or other foreign material. A thin coating of oil normally does not cause poor results, but if optimum-quality welds are required, the material should be degreased before welding. Unclean surface conditions result not only in lack of weld uniformity but also in gas and inclusions in the weld nugget, which reduce weld strength.

Surfaces coated with scale, oxide, oil or other surface films can be more readily projection welded than spot welded. For projection welding on such surfaces, the concentration of the electrode force on the tip of the projection must be sufficient to break through the coating and get the weld started. The heat from this start can then melt and vaporize volatile surface contaminants; other foreign matter is broken up and at least partially expelled during collapse of the projection.

Thin surface films that have low and uniform electrical resistance have the smallest effect on welding. Steel that is coated with extremely thick and nonuniform mill scale may not be weldable on a practical production basis unless the scale is removed prior to welding. (See the section on Surface Preparation on page 415 in the article on Resistance Spot Welding for more detailed information on the effect of surface coatings on welding.)

As workpieces are prepared for projection welding, burrs around sheared edges of the components and around pierced holes in the components should be removed. As the projection collapses, these burrs, if not removed, form shunting paths for both current and electrode force. Uncontrolled shunting makes it difficult to obtain consistently high weld quality.

Process Variables

The major variables that affect projection welding are welding current, electrode force, and weld time. Other factors are heat balance, number and placement of projections, and other aspects of projection and joint design.

Variations in weld quality are minimized when electrode force, welding current, and weld time are maintained at constant values, and when the electrodes are kept clean and in good condition. Other factors that affect the flow of welding current across the weld interface include: quality of power regulation on the high-voltage lines that supply the welding machines, adequacy of low-impedance substation transformers, capacity of bus lines to the welding machines, the use of suitable current or voltage regulators on the welding machines, and proper allowance for the introduction of magnetic metals into the secondary loop of the machine. In addition, accurate fit-up of the workpieces and uniform height of the projections are necessary.

Schedules for projection welding of low-carbon steel from 0.014 to 0.125 in. thick are given in Table 1. These data are intended to serve as starting points, and should be adjusted to suit the specific application and the equipment being used.

Welding current required for projection welding, although slightly less per weld than that needed for spot welding, must be high enough to cause fusion before the projection is completely flattened. The recommended current is the highest current that, when used with the correct electrode pressure, does not cause excessive expulsion of metal. For a specific projection size, expulsion of metal increases as welding current increases, because the current must flow through a small contact area. Slope control sometimes can be used to minimize expulsion.

The rigidity of a projection against collapse, which is a function of work-metal properties and thickness, has an effect on selection of the welding current. For welding thin metal (less than 0.020 in. thick), the ranges of welding current and weld time are narrow.

During a production run, it may not always be feasible (although it is preferred practice) to hold all workpiece variables constant and to avoid heat buildup in the work, electrodes, fixtures and equipment. Therefore, it may be necessary to change the heat-control settings at intervals during the run to produce the desired heat at each weld. (Alternatively, the weld time and the squeeze time can be changed, if more convenient or effective.)

Progressive heat buildup can also be a problem when a number of projection welds are made in sequence on a single part — even though the size and spacing of the projections and the thickness and width of the work metal are the same for all of the welds. Heat buildup can be compensated for by changing the heat-control settings, or otherwise adjusting the current, for some of the welds. In addition, shunting effects may vary after the first weld is made, and heat-sink behavior may differ for some of the welds, which further affect the heat input from weld to weld.

To compensate for such effects in making a number of welds on a single part, suitable changes in heat-control settings can be made manually or can be programed into automatic control equipment for high-production applications, as in the example that follows.

Example 391. Use of Programed Changes in Welding Current To Compensate for Changes in Shunting Behavior and Heat Buildup in High-Speed Projection Welding (Fig. 6)

The brake-shoe assembly shown in Fig. 6 was manufactured by roll forming a rim and a web and joining them with nine projection welds. To compensate for heat buildup and for changes in shunting behavior and thus to provide the desired heat input for each weld, the welding current was increased automatically for successive welds or groups of welds by programed changes in the heat-control setting, as shown in the table with Fig. 6. The machine was equipped with four heat-control units, which were preset at different current levels and were selectively activated by a timer to provide the desired current for each weld.

The web, which had four locating tabs for engagement with slots in the rim, was sheared to shape. The flat rim had, in addition to the four slots, nine weld projections for attachment to the web. Figure 6 shows the detail of the first projection to be welded (Projection A) at the lower left, and the detail of the remaining eight projections (of which Projection B is typical) at the lower right.

Sequence of Operations. The webs and rims were stored in magazines and were fed automatically to the forming and welding machine. In the view at upper right in Fig. 6, the two components are shown in

position at the start of the operation. The electrode wheels (which also served as forming rolls) revolved continuously, and the welding current was initiated by a cam as each projection on the rim came into welding position. The driven electrode wheel had nests for two webs (see Fig. 6), and thus two brake-shoe assemblies were formed and welded at each revolution of the wheel. The web was fed and hydraulically clamped against the driven electrode wheel. Simultaneously, the rim was fed from the second magazine through guides and was advanced until the first slot engaged the first locating tab on the web. The wheel rotated, and as the first projection came into welding position between the electrode wheels and made contact with the web, the welding current was initiated to make the first weld.

As the electrodes revolved and the projections were fed into position against the web, the welds were made in sequence as the rim was formed to the semicircular contour of the web. All movements of the machine were mechanically synchronized; limit switches, closed by cams, initiated the weld timer to make the welds. On completion of the last weld, the assembly was ejected onto a conveyor.

Heat Control and Welding Current. Typical heat-control settings and welding currents for the nine projection welds are shown in the table with Fig. 6. As each weld after the first was made, there was some shunting of current through the preceding weld or welds, making necessary the successive increases in heat-control setting and current. Also, there was a gradual buildup of heat in the work as successive welds were made, which increased the electrical resistance of the work metal and contributed to the need for higher heat-control settings as welding progressed.

The combined effects of shunting and heat buildup were such that a separate heat-control setting was needed for the ninth weld, for which soundness was critical because of its position at an end of the part. At the other extreme, the current at the first projection (which was cool and not subject to shunting) was much lower than for any of the remaining welds, in spite of the fact that the projection for the first weld was more than twice as large in area as the other projections.

Quality Control. Weld quality was checked in three ways: (*a*) the operator peel tested a set of two brake shoes twice during each shift, (*b*) the operator visually spot checked the welds at random intervals during the shift, and (*c*) the quality-control floor inspector visually checked the welds at random intervals during the shift. Welds were acceptable if, when the rim was peeled from the web, a button from the rim remained attached to the web at each weld spot.

The electrode wheels, which were 1¼ in. thick, were removed from the machine and dressed after welding about 6200 assemblies. Equipment details and welding conditions are given in the table with Fig. 6. The procedures described here were used to make other brake-shoe assemblies ranging in diameter from 6½ to 12 in., with rim widths from 1¼ to 2¾ in.

Electrode force used in projection welding depends on the work metal, the size and design of the projection, and the welding machine. Excessive force causes the projection to collapse before the weld area has reached the proper temperature, which results in the formation of ring welds, in which fusion occurs around the periphery of the projection but is incomplete at the center. For best appearance of welds, the electrode force should be such that the projection is flattened completely after the metal has reached welding temperature. Also, force must be sufficient to produce a sound weld with minimum separation of the workpieces.

If the projection is high, a welding machine having heavy, slowly moving parts should not be used, or provision must be made for quick follow-up as the projection is melted. Slow follow-up permits expulsion of molten metal before the pieces can be brought together and welded.

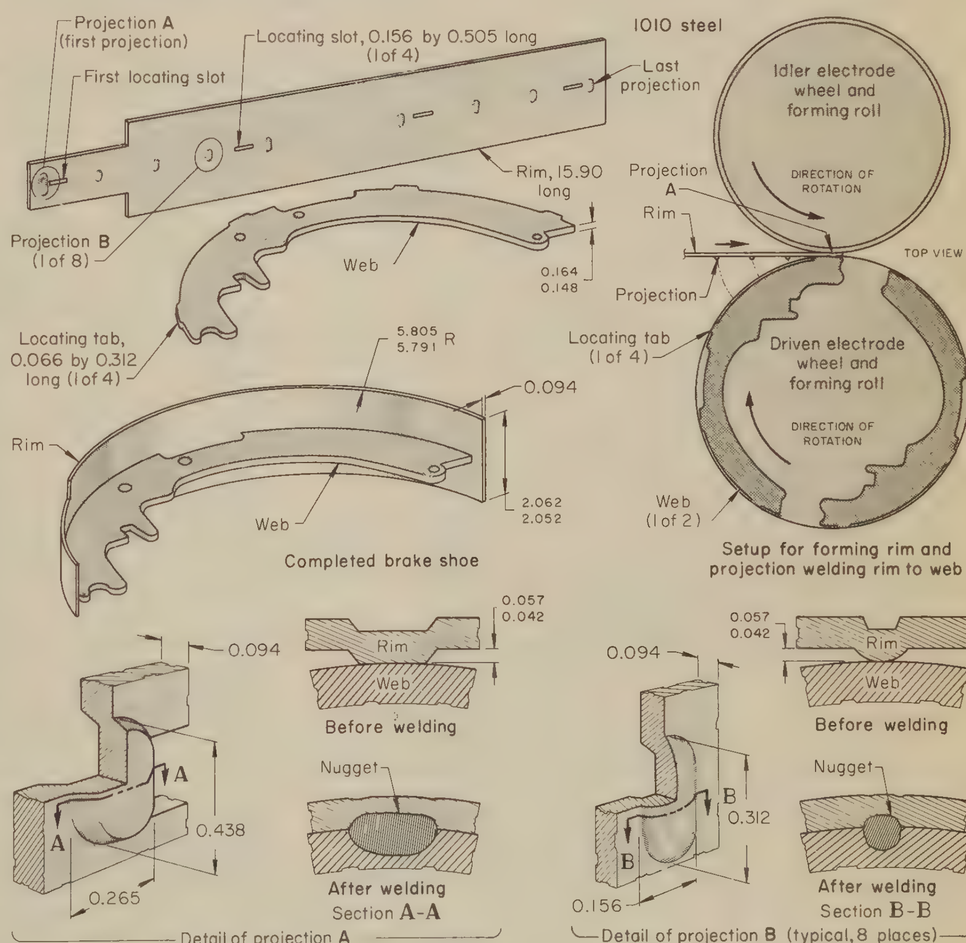
Application of an initial force high enough to cause a definite indentation of the lower workpiece by the projection is sometimes used to help prevent expulsion of molten weld metal when follow-up is too slow or follow-up force is insufficient.

Electrode force influences development of porosity in the weld nugget. The force must be low enough to provide properly timed projection collapse, and yet high enough to produce sound welds. Sometimes, especially in welding thick workpieces, a weld force is used to make the welds, and a forging force is applied after current flow has stopped, to minimize porosity.

Weld time for a given type and thickness of work metal depends on welding current and rigidity of the projection. Weld time is less important than electrode force in projection welding low-carbon and low-alloy steel, provided the time is sufficient to produce a nugget of adequate size at the chosen welding current. A shorter weld time results in higher production efficiency, and in less discoloration and distortion of the workpiece. After the proper electrode force and welding current are determined, the weld time is adjusted to make the desired weld.

Projection welds made in the shortest times are not necessarily of the best quality. A short weld time requires a correspondingly high welding current, which initially must pass through a small contact area, increasing the current density and the possibility of metal expulsion.

When several projection welds are made at once, using the same electrode (multiple-projection welding), it is helpful to use pulsation timing and somewhat longer weld times than for comparable single welds. Variation in height of projections has an effect on timing of initial contact, and the use of slope control provides slow initial heating and allows enough time for all of the projections to make contact with the mating workpiece before the



Equipment Details	
Welding machine	Special automatic
Rating at 50% duty cycle	300 kva
Heat control	16-tap transformer with four heat-control units
Electrode material	RWMA class 2
Electrode force, max	4500 lb

Welding Conditions	
Current, amp	23,000 (weld 1); 28,000 (welds 2-4); 31,000 (welds 5-8); 32,000 (weld 9)
Heat-control settings	65% (weld 1); 80% (welds 2-4); 90% (welds 5-8); 94% (weld 9)
Electrode force	1000 lb
Weld time, each weld	6 cycles

Fig. 6. Brake-shoe assembly that was roll formed and joined with nine projection welds in a special high-speed machine, using progressive increases in welding current to compensate for shunting and heat buildup during welding (Example 391)

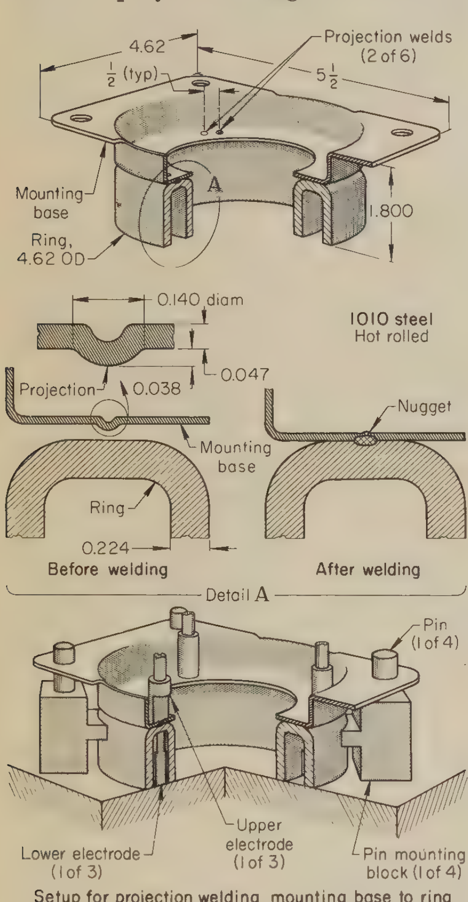
high welding current is applied, thus producing more uniform welds and minimizing expulsion.

Heat Balance. Maintaining the proper heat balance between workpieces sometimes is difficult in projection welding. If heat balance is incorrect, the projection can be melted away before the mating surface is brought to welding temperature.

The factors that affect heat balance are: (*a*) design of the projection, (*b*) electrode material, (*c*) thickness of the workpieces and thermal and electrical conductivity and other properties of the work metals, and (*d*) heating rate.

Projections must be designed to withstand the initial electrode force needed for the proper flow of current, yet collapse fully at welding temperature so as to produce a sound weld with minimum or no sheet separation. When multiple projections in groups of four or more are welded, slight variations in projection height can affect heat balance in all the projections and can make it difficult to obtain simultaneous collapse of the projections.

A water-cooled electrode made of RWMA class 2 or class 3 electrode material may prevent a thin sheet from heating sufficiently if the projection is on a thicker component. This can be avoided by the use of a hard material of low electrical and thermal conductivity, such as RWMA class 10, 11 or 12, in contact with the thinner sheet.



Equipment Details

Power supply .... 440-v 60-cycle ac
Welding machine .... Press type, manually operated, spot and projection
Rating at 50% duty cycle .... 250 kva
Heat control .... Eight-tap transformer and phase shift
Electrode material .... RWMA class 11

Welding Conditions

Welding current .... 42,000 amp
Electrode force .... 2700 lb
Squeeze time .... 35 cycles
Weld time .... 20 cycles
Hold time .... 15 cycles
Assemblies per hour .... 200 (1200 welds)

Fig. 7. Clutch-mount assembly that was projection welded, in the setup shown, using projections that were formed in the thinner workpiece (Example 392)

Table 1. Conditions for Projection Welding of 1010 Steel 0.014 to 0.125 In. Thick Using RWMA Class 2 Electrodes(a)

Thickness of thinnest outside piece, in.(b)	Electrode face diam (min), in.(c)	Net electrode force, lb	Weld time, cycles (60 cps)	Hold time, cycles (60 cps)	Welding current, amp(d)
0.014	1/8	175	7	15	5,000
0.021	5/32	300	10	15	6,000
0.031	3/16	400	15	15	7,000
0.044	1/4	400	20	15	7,000
0.062	5/16	700	25	15	9,500
0.078	3/8	1200	30	30	13,000
0.094	7/16	1200	30	30	14,500
0.109	1/2	1700	30	45	16,000
0.125	9/16	1700	30	45	17,000

SOURCE: "Recommended Practices for Resistance Welding", AWS C1.1; also, "Welding Handbook", 6th Ed., Section 2, American Welding Society, 1969. Published here by permission.

(a) Steel to be welded should be free from scale, oxides, paint, grease and oil. (b) Data based on thickness of thinner sheet, and for two thicknesses only. Maximum ratio between two thicknesses, 3 to 1. (c) Face diameter equals twice the diameter of the projection. (d) Approximate current at electrodes, using 60-cycle ac.

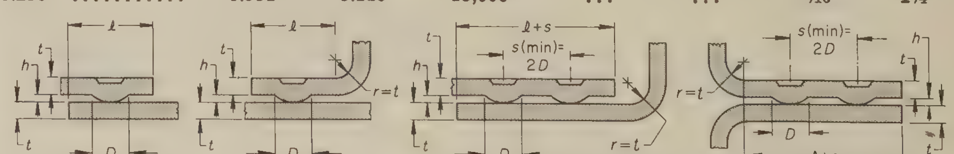
As discussed in the section on Metals Welded, page 438, not all metals can be projection welded, because in some, projections collapse too rapidly under pressure. Also, the thermal conductivity of some metals is such that heat is dissipated away from the projections too quickly for them to reach welding temperature. When dissimilar metals are welded, projections should be formed on the metal of higher electrical and thermal conductivity to more nearly equalize the rate of heating in the two workpieces. Rate of heating is important because the two mating surfaces must be brought to welding temperature at the same time.

When similar metals of equal thickness are welded, projections can be formed on the component that is easier to handle or that has the less critical requirements for surface appearance. In welding workpieces of unequal thickness, projections should preferably be formed on the thicker workpiece to ensure that both of the mating surfaces reach welding temperature at the same time. Projections on the thinner workpiece can melt off before the thicker workpiece reaches welding temperature, unless tooling and welding procedure are specially developed and carefully maintained and controlled to overcome this problem.

However, with suitable precautions, good results can be obtained using projections formed on the thinner workpiece — even when the workpiece-thickness ratio is as great as 5 to

Table 2. Details of Design of Projection Welds in Low-Carbon and Stainless Steels(a)

Thickness (*t*) of thinnest outside piece, in.(b)	Diameter of projection *D*, in.(c)	Height of projection *h*, in.(d)	Minimum shear strength (single projections only), lb — Tensile strength below 70,000 psi	Tensile strength 70,000 to 150,000 psi	Tensile strength 150,000 psi and above	Nugget diameter (min) at weld interface, in.	Minimum contacting overlap *l*, in.(e)
0.010	0.055	0.015	130	180	250	0.112	1/8
0.012	0.055	0.015	170	220	330	0.112	1/8
0.014	0.055	0.015	200	280	380	0.112	1/8
0.016	0.067	0.017	240	330	450	0.112	5/32
0.021	0.067	0.017	320	440	600	0.140	5/32
0.025	0.081	0.020	450	600	820	0.140	3/16
0.031	0.094	0.022	635	850	1100	0.169	7/32
0.034	0.094	0.022	790	1000	1300	0.169	7/32
0.044	0.119	0.028	920	1300	2000	0.169	9/32
0.050	0.119	0.028	1,350	1700	2400	0.225	9/32
0.062	0.156	0.035	1,950	2250	3400	0.225	3/8
0.070	0.156	0.035	2,300	2800	4200	0.281	3/8
0.078	0.187	0.041	2,700	3200	4800	0.281	7/16
0.094	0.218	0.048	3,450	4000	6100	0.281	1/2
0.109	0.250	0.054	4,150	5000	7000	0.338	5/8
0.125	0.281	0.060	4,800	5700	8000	0.338	11/16
0.140	0.312	0.066	6,000	...	...	7/16	3/4
0.156	0.343	0.072	7,500	...	...	1/2	13/16
0.171	0.375	0.078	8,500	...	...	9/16	7/8
0.187	0.406	0.085	10,000	...	...	9/16	15/16
0.203	0.437	0.091	12,000	...	...	5/8	1
0.250	0.531	0.110	15,000	...	...	11/16	1 1/4



SOURCE: "Recommended Practices for Resistance Welding", AWS C1.1; also, "Welding Handbook", 6th Ed., Section 2, American Welding Society, 1969. Published here by permission.

(a) Welding conditions in table are for 1010 steel, and for types 309, 310, 316, 317, 321 and 347 stainless steel. Surface of steel to be welded should be free from scale, oxides, paint, grease and oil. (b) Size of projection is normally determined by thickness of thinner piece, and projection should be on thicker piece where possible. Data are based on thickness of thinner sheet, and for two thicknesses only. (c) Projection should be made on workpiece of higher conductivity when dissimilar metals are welded. For diameter of projection *D*, a tolerance of ±0.003 in. in material up to and including 0.050 in. in thickness and ±0.007 in. in material over 0.050 in. in thickness may be allowed. (d) For height of projection *h*, a tolerance of ±0.002 in. in material up to and including 0.050 in. in thickness and ±0.005 in. in material over 0.050 in. in thickness may be allowed. (e) Contacting overlap *l* does not include any radii from forming. Weld should be located in center of overlap.

1, as in the following example, in which forming of projections on the thicker workpiece was too difficult.

Example 392. Projection Welding of a Steel Assembly in Which the Projections Were Formed on the Thinner Workpiece (Fig. 7)

The clutch mount for the compressor in an automobile air conditioner was made by projection welding a drawn ring with a 0.224-in.-thick wall to a mounting base 0.047 in. thick (see Fig. 7). Both components were made of 1010 steel. In the original design of the assembly, the projections were on the thicker (ring) section, as conventionally recommended. However, these projections were difficult to form, and the assembly was redesigned with the projections on the thinner (base) section. With the new design, satisfactory welds were made without burning the thin mounting base. Equipment details and welding conditions are given in the table with Fig. 7.

The projections were formed in pairs 120° apart on the contact surface of the mounting base. The projections in each pair were ½ in. apart.

The outside diameter of the ring was required to be concentric with the bolt circle on the mounting base within 0.010 in. TIR. This requirement was met by use of the fixture shown in Fig. 7. Four pins that extended upward from mounting blocks positioned on the base of the fixture passed through locating holes in the mounting base, while machined inner faces on the pin-mounting blocks located the outside diameter of the ring. To maintain the specified tolerances on the assembly, the outside diameter of the ring had to be held within ±0.005 in. in the forming operation. The diameter of the locating holes was held to +0.002, −0.001 in., and the diameter of the bolt circle was held to ±0.001 in.

The three upper electrodes were lowered to make the six welds simultaneously.

The finished assemblies were visually examined for weld nuggets. Destructive tests were made on two assemblies per hundred. For acceptance, five welds on each assembly tested had to pull buttons. The rejection rate due to weld failures was negligible. Assemblies were inspected for compliance with the concentricity requirement in a rotating fixture using a dial indicator. Samples were inspected on the basis of a 5% acceptable quality level. The welded assemblies consistently remained within tolerance, provided the components were within their assigned manufacturing tolerances.

Welding Schedules. Practice in setting up welding schedules for projection welding of work for which previous experience is lacking is generally the same as for resistance spot welding. A typical sequence of steps is described on page 417 in the article on Resistance Spot Welding.

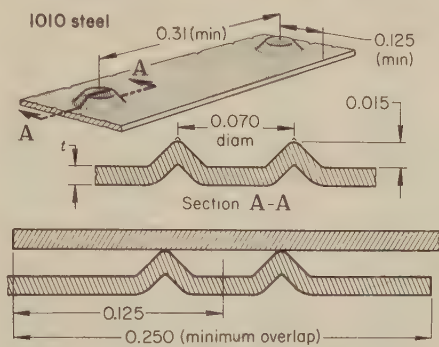
Tables 1 to 7 in the present article give data on recommended practices for projection welding of low-carbon steel, which are intended to serve as starting points. (Table 2, which gives details of projection design, applies also to austenitic stainless steel.)

Electrodes, Welding Dies and Fixtures

An electrode designed for resistance spot welding can be used for projection welding if the electrode face is large enough to cover the projection being welded, or the pattern of projections being welded simultaneously, by the electrode. To minimize marking and indentation of workpieces, recommended electrode-face diameter for making a single projection weld usually is two or more times the diameter of the projection; in multiple-projection welding, the electrode face should be large enough to extend beyond the boundaries of the pattern of projections by approximately the diameter of one projection.

Table 3. Conditions and Joint Strength for Projection Welding Thin 1010 Steel Sheets of Equal Thickness, Using Annular Projections (a)

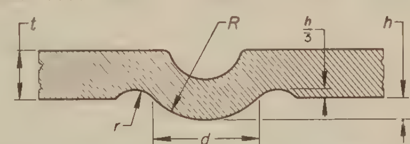
Item	Sheet thickness (t), in. 0.0105	0.0179
Weld time, cycles	6	6
Electrode force, lb	110	225
Welding current, amp	5200	5400
Breaking load of joint in shear test, lb:		
One projection	190	400
Two or more projections (b)	145	280



(a) Surface of steel may be oiled slightly, but should be free of grease, scale and dirt. (b) Approximate strength of joint at each projection. (SOURCE: Same as for Table 4)

Table 4. Dimensions of Recessed Projections for Welding of Low-Carbon Steel 0.123 to 0.245 In. Thick

Steel thickness, t, in.	Dimensions of projection, in. Height, h, ±2%	Diameter, d, ±5%	Spherical radius, R	Inside radius, r
0.123	0.058	0.270	0.196	0.065
0.135	0.062	0.300	0.215	0.072
0.153	0.064	0.330	0.235	0.078
0.164	0.068	0.360	0.248	0.083
0.179	0.080	0.390	0.274	0.091
0.195	0.084	0.410	0.286	0.095
0.210	0.090	0.440	0.305	0.101
0.225	0.100	0.470	0.325	0.108
0.245	0.112	0.530	0.365	0.121



SOURCE: J. F. Harris and J. J. Riley, "Projection Welding Low-Carbon Steel Using Embossed Projections", *Welding Journal*, Apr 1961; reprinted as RWMA Bulletin No. 31

Simultaneous welding of a number of projections that are far apart requires a rigid electrode large enough to cover the projections and shaped so as not to deform tabs, flanges or other features of the component being welded. The use of a pivoted electrode that is properly designed and insulated to avoid excessive shunting may be helpful in some applications, as in Example 388. With proper fixturing, the accuracy attainable with projection welding is equal to that obtained with any other joining process.

Electrode Materials. Flat electrodes or local contact-surface electrodes usually have acceptable life when made from RWMA class 2, 3 or 4 materials. (See Tables 2 and 3, page 409, in the article on Resistance Spot Welding, for identification of electrode materials.) RWMA class 2 electrode materials are generally preferred because they provide the best compromise among electrical conductivity, strength, hardness, and temperature resistance.

If a harder electrode material or a material with lower electrical conductivity is needed, an economical solution is to use a composite electrode with copper backing and a copper-tungsten alloy facing. The facing material usually is RWMA class 10, 11 or 12. Classes 11 and 12 have lower electrical conductivity and higher hardness and strength than does class 10.

The ideal electrode material is one that is as hard as possible and that does not crack or cause surface burning on the weldment. If cracking or surface burning is encountered, a softer alloy with higher conductivity and ductility should be used.

In the examples in this article for which electrode materials are given, class 2 material was used in eleven applications, class 3 in six, class 11 in four and class 10 in one. (In some applications, upper and lower electrodes or inserts were of different materials.)

Table 5. Projection Dimensions and Welding Conditions for Projection Welding of Low-Carbon Steel 0.153 to 0.245 In. Thick (a)

Steel thickness, in.	Projection size: Diameter, in.	Height, in.	Projection spacing (min), in.	Contacting overlap (min), in.	Electrode force, lb: Weld	Forge	Upslope time, cycles	Weld time, cycles	Welding current, amp	Shearing load of joint, lb (b)
Normal-Size Projections										
0.153	0.330	0.062	1.75	0.90	2000	4000	15	60	15,400	7,500
0.164	0.350	0.068	1.80	0.95	2300	4600	15	70	16,100	8,100
0.179	0.390	0.080	1.90	1.00	2630	5260	20	82	17,400	9,500
0.195	0.410	0.084	2.00	1.05	2930	5860	20	98	18,800	11,300
0.210	0.440	0.092	2.10	1.15	3180	6360	25	112	20,200	12,500
0.225	0.470	0.100	2.30	1.20	3610	7220	25	126	21,500	15,000
0.245	0.530	0.112	2.50	1.30	3900	7800	30	145	23,300	17,300
Small-Size Projections										
0.153	0.270	0.058	1.60	0.75	1400	2800	15	60	11,100	5,100
0.164	0.290	0.062	1.65	0.80	1425	2850	15	70	11,800	5,500
0.179	0.310	0.067	1.70	0.85	1500	3000	20	82	12,800	6,500
0.195	0.330	0.072	1.75	0.90	1600	3200	20	98	13,900	7,700
0.210	0.350	0.077	1.80	0.95	1730	3460	25	112	14,900	8,500
0.225	0.370	0.082	1.90	1.00	1870	3740	25	126	16,000	10,400
0.245	0.390	0.088	2.10	1.10	2100	4200	30	145	17,300	12,000

(a) For welding two equal thicknesses of metal. As thickness ratio increases, welding current and weld time are increased to obtain a sufficiently large nugget diameter and adequate penetration, and to minimize sheet separation. (b) Approximate shear strength of joint for each projection weld; shear strength varies with joint design. (SOURCE: Same as for Table 4)

Electrode Design. There are three basic types of electrodes used in projection welding:

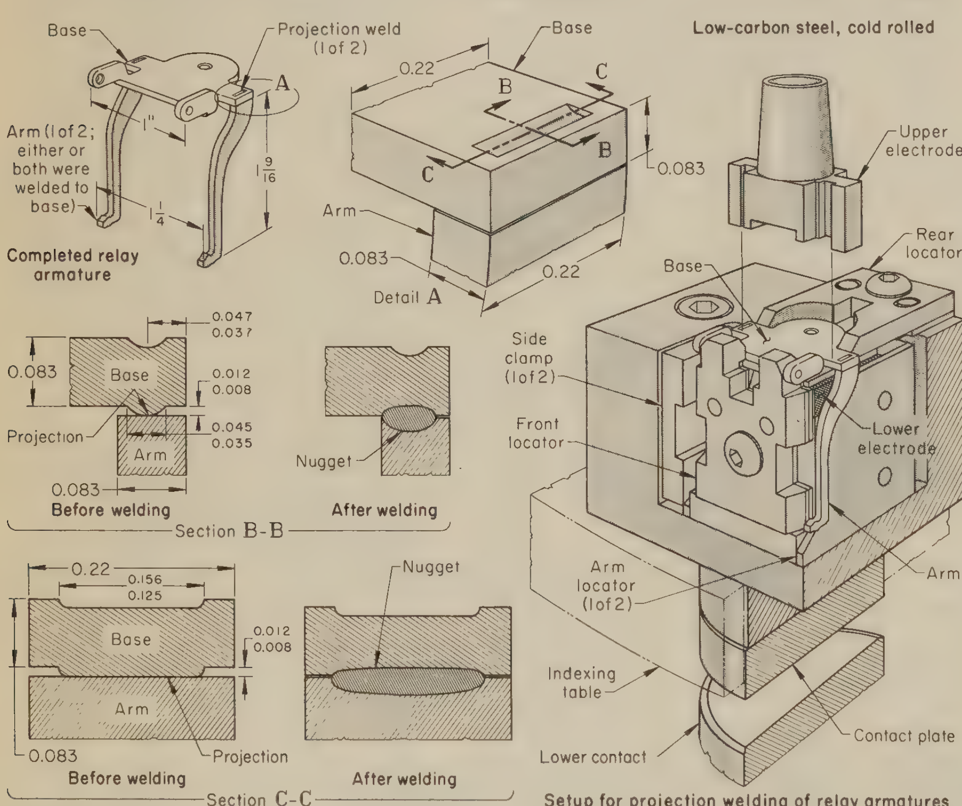
1 Round, flat-face electrodes of the type used for spot welding
2 Large, flat-face electrodes of bar stock
3 Bar-type electrodes, in which a series of local-contact surfaces are made by relieving the bar between intended contact locations, or by brazing or clamping contact inserts of hard copper alloy to the bar. (Figures 2, 18 and 20 show electrodes of this type.)

Table 6. Conditions for Cross-Wire Welding of Low-Carbon Steel Wire

Wire diameter, in.	Weld time, cycles (b)	Conditions for 15% setdown(a): Electrode force, lb	Welding current, amp	Weld strength, lb	Conditions for 30% setdown(a): Electrode force, lb	Welding current, amp	Weld strength, lb	Conditions for 50% setdown(a): Electrode force, lb	Welding current, amp	Weld strength, lb
Cold Drawn Wire										
1/16	5	100	600	450	150	800	500	200	1,000	550
1/8	10	125	1,800	975	260	2,650	1,125	350	3,400	1,250
3/16	17	360	3,300	2,000	600	5,000	2,400	750	6,000	2,500
1/4	23	580	4,500	3,700	850	6,700	4,200	1240	8,600	4,400
5/16	30	825	6,200	5,100	1450	9,300	6,100	2000	11,400	6,500
3/8	40	1100	7,400	6,700	2060	11,300	8,350	3000	14,400	8,800
7/16	50	1400	9,300	9,600	2900	13,800	11,300	4450	17,400	11,900
1/2	60	1700	10,300	12,200	3400	15,800	13,600	5300	21,000	14,600
Hot Drawn Wire										
1/16	5	100	600	350	150	800	400	200	1,000	450
1/8	10	125	1,850	750	260	2,770	850	350	3,500	900
3/16	17	360	3,500	1,500	600	5,100	1,700	750	6,300	1,800
1/4	23	580	4,900	2,800	850	7,100	3,000	1240	9,000	3,100
5/16	30	825	6,600	4,600	1450	9,600	5,000	2000	12,000	5,300
3/8	40	1100	7,700	6,200	2060	11,800	6,800	3000	14,900	7,200
7/16	50	1400	10,000	8,800	2900	14,000	9,600	4450	18,000	10,200
1/2	60	1700	11,000	11,500	3400	16,500	12,400	5300	22,000	13,000

SOURCE: "Resistance Welding Manual", 3rd Ed., Vol 1, p 88, Resistance Welder Manufacturers' Association, 1956 (reprinted 1959)

(a) Setdown is the amount a wire is embedded into another wire during resistance welding. (b) For 15%, 30% and 50% setdown.



Equipment Details	
Welding machine	440 v, single phase, automatic
Rating at 50% duty cycle	30 kva
Current, max	30,000 amp
Secondary voltage	2.4 to 4.8 v
Electrode material	RWMA class 2
Electrode force, max	550 lb
Heat control	Eight-tap transformer and phase shift
Auxiliary equipment	Rotary-indexing table with loading and unloading devices

Item	Single arm	Double arm
Welding Conditions		
Welding current, amp	3400	4400
Secondary voltage, v	2.7	3.1
Heat-control setting, %	80	86
Electrode force, lb	115	160
Clamp force, lb	50	50
Squeeze and hold times, cycles	6 each	6 each
Weld time, cycles	5	6
Production, assemblies per hr	1500	1500
Production, welds per hr	1500	3000

Fig. 8. Setup for automatic projection welding of one or two arms to a base in the manufacture of relay armatures (Example 393)

Standard spot welding electrodes are used to weld single projections; electrode diameter is usually at least twice that of the projection.

Large flat-face electrodes are used for welding a few projections in a localized area, but they are not recommended for welding components that may be distorted from the projection-forming operation.

Bar-type electrodes usually can equalize current and force regardless of slight distortion or other variations in the workpieces, and are recommended for all multiple-projection welding, especially in applications that involve four or more projections.

Welding Dies and Fixtures. Welding dies hold and clamp the workpieces in correct alignment for welding, and also serve as electrodes or as holders for inserted electrodes or electrode buttons. Fixtures are auxiliary positioning devices that do not conduct current.

Welding dies and fixtures should be designed to meet these requirements:

1 Accurately position the workpieces.
2 Permit rapid loading and unloading. Air jets, levers or mechanical loading and unloading devices can be used. A combination of manual loading and automatic unloading is employed in many applications.
3 Allow initial workpiece contact at or near the weld, to provide the shortest possible current path between the electrodes, and to avoid energy losses from unnecessary resistive heating of thin sections of work metal in the current path.

Steel or other magnetic materials should not be used in fixtures for welding with alternating current, because they reduce the electrical capacity of the machine and heat up when within the secondary loop. Nonmetallic materials that have good strength and are electrical insulators, such as filled phenolics, help to avoid unintentional shunting of current, and are often used in fixturing for small parts.

Small parts can be located by the lower die, and larger parts by stops, pins or other types of locators. When a small part is to be located on top of a larger part, a removable gage can be used that locates the parts while the upper die makes the weld. Parts also can be held in the upper die by spring clips, plungers or vacuum.

Projection welding of assemblies that have long, thin components may demand special care in the design of fixtures. Heating must be concentrated at the weld interface, and to avoid waste of energy and overheating of workpieces, fixtures should be designed to provide electrode contact to the long, thin component as close as possible to the joint, as in the following example.

Example 393. High-Production Welding of a Relay Armature in Which Electrical Contact Was Made Near the Joint Surface To Prevent Overheating of Long, Thin Arms (Fig. 8)

The relay armature shown at upper left in Fig. 8 was made by projection welding the two arms to the formed base. Some of these armatures required only one arm, on either the left or the right side.

Fixtures for locating and clamping the components in proper relation were mounted on a rotary-indexing table (see view at right in Fig. 8), and an automatic welding

machine was designed that was capable of projection welding either or both arms to the armature base at a rate of 1500 assemblies per hour. The sequence of operations performed by the machine was as follows:

1 Load a left arm, a right arm or both arms into the fixture.
2 Detect presence of arm or arms.
3 Load base into fixture.
4 Detect presence of base.
5 Clamp components in fixture and weld.
6 Unload welded assembly.

During welding, air-actuated side clamps held the arms against the lower electrode, which was ¼ in. thick. Below this electrode, the fixture was recessed to restrict the current flow to the joint end of the arms. The cross-sectional area of the lower portions of the arms was not large enough to carry the welding current, and this arrangement minimized heat losses.

The upper electrode, shaped as shown in Fig. 8, was attached to the lower end of a spring-loaded inner shaft of an air-actuated ram on the welding machine. This low-inertia, fast-follow-up welding head, similar to that shown in Fig. 5, provided a precisely timed follow-up to complete the weld, and avoided undesirable arcing.

To help concentrate the welding current at the joint, an elongated projection was formed on the base in the area where each arm was to be attached (see sections B-B and C-C in Fig. 8). The sheared edges on the arm assisted in making a good weld.

The dimensions of the assemblies were checked after each lot of 500 had been welded. The welds were tested by bending the arms to the side or by twisting them; other destructive tests were made after each lot of 500 assemblies to determine tensile strength. Minimum breaking load was specified at 150 lb for each weld. The joints were tested to a load of 300 lb. If a weld failed in the range of 150 to 300 lb, the nugget was required to pull base metal over at least 50% of its area.

Equipment details, and conditions for welding single-arm and double-arm assemblies, are given in the table that accompanies Fig. 8. The electrode force, current and weld time were established to produce a weld nugget with a strength of 200 lb. The upper electrode was changed after welding each lot of 5000 assemblies.

Table 7. Conditions for Projection Welding of Galvanized Steel Using Class 2 Electrodes(a)

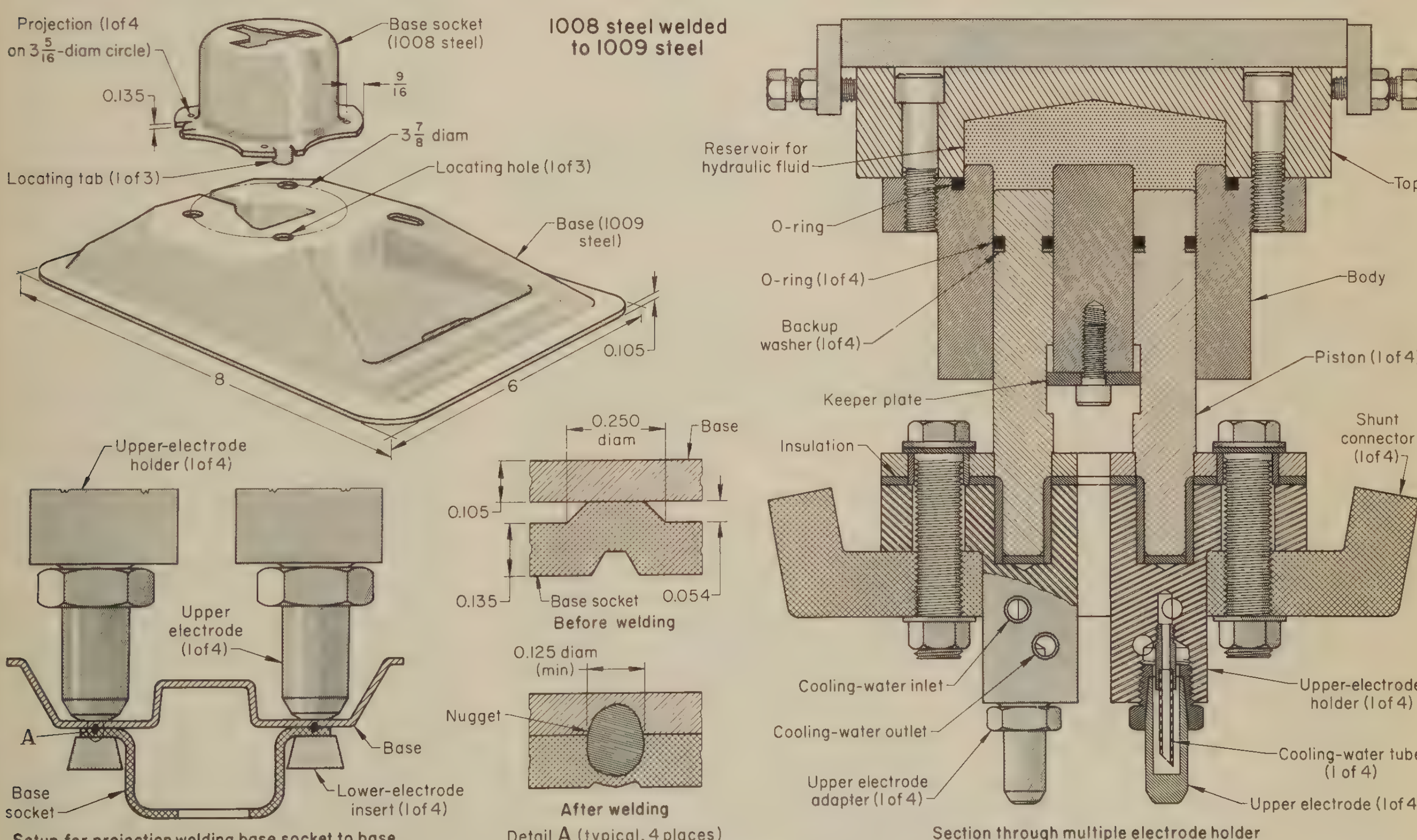
Thickness of each steel piece, in.(b)	Electrode dimensions: Body diameter, in.	Electrode dimensions: Face diameter, in.	Net electrode force, lb	Weld time, cycles	Welding current (approx), amp	Diameter of projection, in.	Height of projection, in.	Nugget diameter, in.	Minimum tension-shear strength, lb(c)
0.039	⅝	⅜	250	15	10,000	0.187	0.041	0.15	925
0.063	⅝	7/16	400	20	11,500	0.218	0.048	0.25	2050
0.078	¾	½	550	25	16,000	0.250	0.054	0.25	2700
0.093	¾	½	750	30	16,000	0.250	0.054	0.30	4300
0.108	⅞	½	950	33	22,000	0.250	0.054	0.31	4900

SOURCE: "Recommended Practices for Resistance Welding Coated Low-Carbon Steels", AWS C1.3-70, American Welding Society, 1970. Published here by permission.

(a) Data are for welding galvanized steel with a commercial-weight coating of 1.25 oz per square foot. Steel to be welded must be free from dirt, grease and paint, but may have a light coating of oil. (b) Data are for welding two pieces of equal thickness. (c) For single projections only.

Electrode Holders. In projection welding, electrodes are placed in holders similar to those used in resistance spot welding. The holders are for single electrodes, or for two or more electrodes. Holders for single electrodes can be used for both the upper and lower electrodes. Multiple-electrode holders, of either standard or special design, are generally used for the upper electrodes; electrode forces are equalized by springs, mechanical devices or hydraulic equalizers.

Hydraulic equalizers will transmit high forces equally to electrodes that are spaced closer than is permissible with mechanical linkage or spring-type balancers. The amount of electrode force that can be transmitted through mechanical or spring-type equalizers generally is low. Also, it is difficult to adjust spring-type equalizers so that the same force is exerted on the workpiece through each electrode. When electrode forces greater than about



Equipment Details

Welding machine .... Special semiautomatic arch type, with four eight-tap transformers
Rating at 50% duty cycle .... 75 kva each
Current per electrode, max .... 12,300 amp
Secondary voltage .... 6.1 to 10 v
Upper electrodes .... RWMA class 2
Lower electrode inserts .... RWMA class 11
Force per electrode, max .... 2825 lb

Welding Conditions

Current per electrode .... 8,000 to 10,000 amp
Transformer tap settings .... No. 1 or No. 2
Force per electrode .... 2400 lb
Squeeze time .... 10 cycles
Weld time .... 11 cycles
Hold time .... 3 cycles
Production rate:
Assemblies per hour 750
Welds per hour 3000

Fig. 9. Projection welding of an automobile-jack base, in which a specially designed hydraulic-equalizing multiple-electrode holder was used to make four closely spaced welds simultaneously under high electrode force (Example 394)

1000 lb are used, the size of the spring and holder can limit the minimum center distance between the electrodes.

For the application in the next example, a special hydraulic-actuated multiple-electrode holder was designed that would equalize the high electrode force while making four closely spaced projection welds in thick workpieces.

Example 394. Use of a Specially Designed Multiple-Electrode Holder To Make Four Welds Simultaneously Under High Electrode Force (Fig. 9)

A base for an automobile jack was made as a projection weldment of two press-formed components: a base socket of 0.135-in.-thick 1008 steel, and a base of 0.105-in.-thick 1009 steel (see Fig. 9). Four projections were formed on a 3$\frac{9}{16}$-in.-diam circle on the lower side of the base socket.

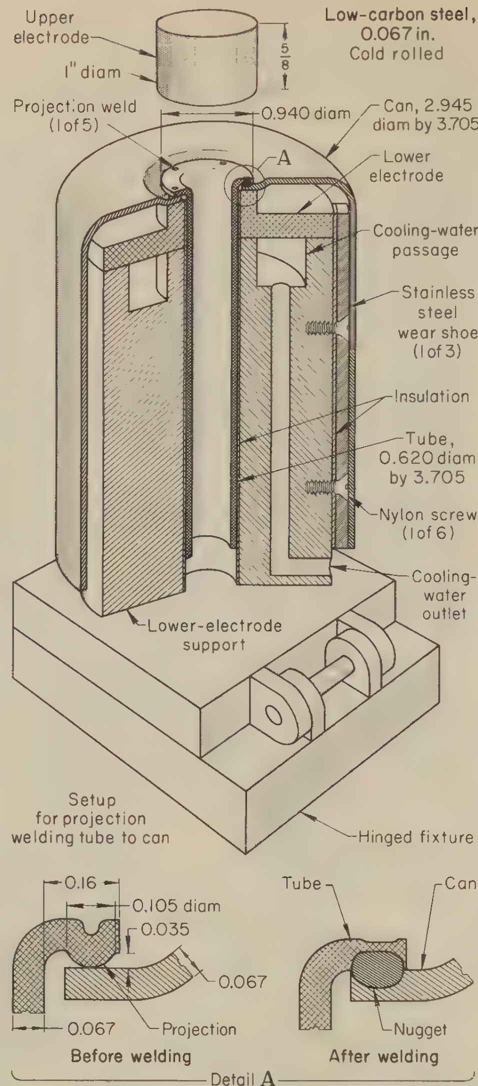
Because the spacing of the projections was comparatively close for simultaneous welding with electrodes in separate holders, and because the thick work metal required use of high electrode force, a special welding machine with a hydraulic-equalizing upper-electrode holder that contained four electrodes was designed. Each of the electrodes was connected to a separate transformer, and all four welds were made simultaneously. The four transformers had a common ground attached to the lower-electrode assembly.

Force for all four upper electrodes was provided by a single air cylinder. The hydraulic equalizer consisted of a main chamber with four pistons arranged in a keystone-shape pattern coinciding with that of the four projections (approximately 2$\frac{3}{8}$ in. apart). Each piston was hardened and contained an O-ring and a leather backup washer. A hardened keeper-plate limited piston travel and prevented rotation of the piston due to pull from the inductive field created by the adjacent electrode feeder shunts. A flange on the end of each piston was used for attaching a copper alloy electrode holder. Fiber bushings and washers electrically isolated the electrode holder from the piston. The top contained a reservoir for the hydraulic fluid and was fastened to the piston rod of the air cylinder. The equalizing head was initially charged with molten petroleum jelly to facilitate bleed-off of entrapped air. Replacement of the petroleum jelly was done through a high-pressure grease fitting using a grease gun. A needle-type shutoff valve protected the grease fitting from the high operating pressure. Petroleum jelly was used as the hydraulic fluid because it was viscous enough to keep the piston from moving too far from working position between strokes but not viscous enough to extend unduly the time needed to balance the force during the working stroke.

The upper electrodes, made of RWMA class 2 material, were attached to the holders through adapters that provided for water cooling of the electrodes. The lower electrode was a large copper block with replaceable inserts of RWMA class 11 material (copper-tungsten alloy) under each weld location. The lower-electrode block had a locator for positioning the base socket. Although the components had matching tabs and holes for final location, the frame for an automatic unloading device was used as an approximate locator when the base was placed on top of the base socket.

The assembly was welded in the inverted position, as shown in Fig. 9. Equipment details and welding conditions are given in the table with Fig. 9. Production rate was 750 pieces per hour.

The welds were tested several times each hour by inserting a wedge between the welded surfaces with a hydraulic jack. The separated nuggets were required to be at least $\frac{1}{8}$ in. in diameter.



Equipment Details

Power supply	440-v 60-cycle ac
Welding machine	Press type, spot and projection, with air-operated ram
Rating at 50% duty cycle	200 kva
Heat control	Eight-tap transformer and phase shift
Electrode material	RWMA class 3

Welding Conditions

Welding current	32,000 amp
Electrode force	2000 lb
Squeeze time	15 cycles
Weld time	26 cycles
Hold time	10 cycles
Off time	10 cycles
Assemblies per hour	200 (1000 welds)

Fig. 10. Projection welding of a can to a tube, in which cooling-water passage in lower-electrode support was enlarged to prevent overheating of lower electrode in continuous production (Example 395)

Current Path. Arrangement of work, projections, electrodes and fixtures so as to provide the shortest possible current path from one electrode through the work at the desired weld point to the other electrode, as in Example 395, is also important in the projection welding of bar stock to sheet metal, as shown in Examples 396, 397 and 407.

Cooling of Electrodes and Dies. Water cooling, either directly on or within the electrode or die, is used to avoid overheating of dies and workpieces. The water passages should be located as close as possible to the face of the electrode (or the die) without weakening this component.

In projection welding, the rate of operation of the equipment has an important bearing on the quality of the welds produced. If the equipment, especially welding dies and electrodes, does not have sufficient cooling time between welds, the quality of welds deteriorates as the equipment gets hotter. Equipment must be able to dissipate at least as much heat as is generated by the welding process. This can be arranged by the often undesirable expedient of slowing the production rate to increase the cooling part of the cycle. If the production rate must be maintained, the passages for cooling water in the electrodes can be enlarged, as long as adequate electrode strength is retained, as was done in the example that follows.

Example 395. Use of an Enlarged Cooling-Water Passage To Limit Heat Buildup in a Lower Electrode (Fig. 10)

Five projection welds were made simultaneously in joining a flanged tube and a deep drawn can, as shown in Fig. 10. Equipment details and welding conditions are given in the table that accompanies Fig. 10.

The current (32,000 amp) needed to make the five welds simultaneously produced more heat in the lower electrode than could be dissipated in continuous production at the required rate of 200 assemblies per hour, and the lower electrode burned out after making 400 to 500 assemblies, or in a little more than 2 hr. When time was taken to change electrodes, the production rate could not be maintained.

To prevent overheating, the cooling-water passage in the support for the lower electrode was enlarged.

The upper electrode was a simple cylinder of RWMA class 3 material, 1 in. in diameter and $\frac{5}{8}$ in. thick, and was attached to a swivel mounting. Both the lower electrode and the lower-electrode support, mounted on a fixture that could be rocked out on a hinge to change workpieces, were annular in shape to fit the space between the can and the tube. Insulation prevented contact between the lower-electrode assembly and the tube, and three insulated stainless steel wear shoes were used for locating the can. The insulated shoes were fastened to the lower-electrode support with nylon screws. Electrodes were removed and re-dressed after every 4000 assemblies, or after every 20 hours of operation, and were re-dressed two or three times before being replaced.

Each assembly was visually inspected for fusion at each projection. A full weld nugget was required on at least two of the five projections. No definite scrap rate was established because the rate was so low.

Projections

The size and shape of projections depend on the application and the required weld strength. Properly proportioned projections localize or concentrate the welding current, accurately control the location of welds, and ensure uniformity of weld nuggets. Projections often are spaced to give a three-point bearing. Three projections readily equalize themselves and give uniform contact with the mating workpiece if the electrodes are in reasonable alignment. For best results, the three projections usually are equally spaced and, on circular workpieces, are located radially, as far as possible from the axis of the workpiece.

Design of Projections. Proper projection design helps to provide consistent results and to reduce breakage of

forming tools. Following are some criteria for designing projections:

1 They should be easy to form without distorting the workpiece.
2 When projections are formed in sheet-metal parts, the metal in and around the projection must not be cracked or made markedly thinner.
3 The projection should be strong enough to support the initial electrode force before the current is applied.
4 The projection should collapse during welding without excessive expulsion of metal, leaving the two components in intimate contact.

Types of Projections. The five basic types of projections — spherical, elongated, annular, pyramidal and cross-wire — are shown in Fig. 11, along with two special types of projection welds for which conventional projections are not used. All types will produce strong welded joints if properly selected and applied.

Spherical projections are recommended for welding assemblies made of steel sheet and plate. They also can be coined or forged on the ends or faces of screws, nuts and similar fasteners. Several projections can be used, as in Fig. 11(b), or a single large, gently radiused projection can cover the entire face of the mating workpiece, as in Fig. 11(c). Details of size, overlap and strength of conventional spherical projections are given in Table 2. Recessed spherical projections are shown in the illustration accompanying Table 4, page 441, which gives dimensions for recessed projections used in welding steels of different thicknesses.

Elongated projections often are used instead of spherical projections where the shape of the parts makes an elongated weld more suitable, and where welds made with spherical projections will not meet strength requirements. For a given work-metal thickness, the height of an elongated projection should be approximately the same as the height of a spherical projection, the width should be approximately equal to the diameter of a spherical projection, and the length should be made to suit the application — usually two to three times the width.

Figure 11(d) shows an elongated projection that has been embossed in a sheet metal part. This type of projection was used in welding the flat base of a relay armature to the 0.083-by-0.22-in. end of the relay arm in Example 393, and in welding the rim of a brake-shoe assembly to the edge of a 5⁄32-in.-thick web in Example 391. The use of elongated projections on sheet metal that is to be welded to the sidewall of a tube or other cylindrical workpiece is described on page 447 and illustrated in Fig. 14. Elongated projections also can be coined or forged on fasteners, as in Fig. 11(e). Another type of elongated projection, of which the full width and height extend to the edge of a sheet metal part that is to be welded to the edge of a mating part, is shown in Fig. 11(f).

Annular projections are used for welding tubing to sheet metal, as shown in Fig. 11(g). (See Fig. 15, and the section on Projection Welding of Tube to Sheet Metal, page 447.) Annular projections are also used for joining sheet metal parts, particularly thin parts, where spherical projections may collapse prematurely during welding (Fig. 11h), and for making liquid-tight or gastight connections, as in attaching mounting studs to housings (Example 407). Accurate alignment of electrode faces is especially critical when annular projections are used.

In welding bar stock or screw-machine parts to sheet or plate in a joint such as the one shown in Fig. 11(j), the shape of the parts in the annular region of contact serves the function of a conventional projection.

Pyramidal projections coined or forged on the face of a nut are shown in Fig. 11(k) and (m).

Cross-wire welds (Fig. 11n) are used in making various wire products. No separate projection is formed; the shape of the wires produces point contact where the wires intersect, and functions as a projection. (See the discussion in the section on Cross-Wire Welding, page 448.) Round wire is welded to flat stock, using line contact.

In addition to cross-wire welds (as shown in Fig. 11n and Examples 398, 399, 403 and 404) and annular welds on pin-and-tenon joints (as shown in Fig. 11j and Examples 396 and 397), other types of joints also can be projection welded without the use of conventional projections. In Example 406, the curved outer surface of a steel tube functioned as a projection in welding the tube to the flat end of a cylindrical slug.

Spacing of Projections. The minimum spacing of projection welds can be somewhat less than that of spot welds because during projection welding the current is concentrated on a smaller area. The minimum spacing between projections is twice the projection diameter. A spacing substantially greater than the minimum is often used, to make embossing of the projections easier.

As shown in Tables 2 and 5, the recommended minimum contacting overlap for projection welding is from 2.3 to 2.8 times the projection diameter.

Projection Welding of Sheet Metal Parts

The principal uses of projection welding are those in which blanked, stamped and formed sheet metal parts are joined with the aid of projections that have been produced during the stamping or forming operation. Spherical and elongated projections are the types most commonly used for welding sheet metal parts; however, annular projections are used in welding parts less than 0.020 in. thick and in applications where gastight or liquid-tight connections are needed.

Thin workpieces, from 0.010 to 0.021 in. thick, can be projection welded using carefully designed projections and welding machines that have rapid

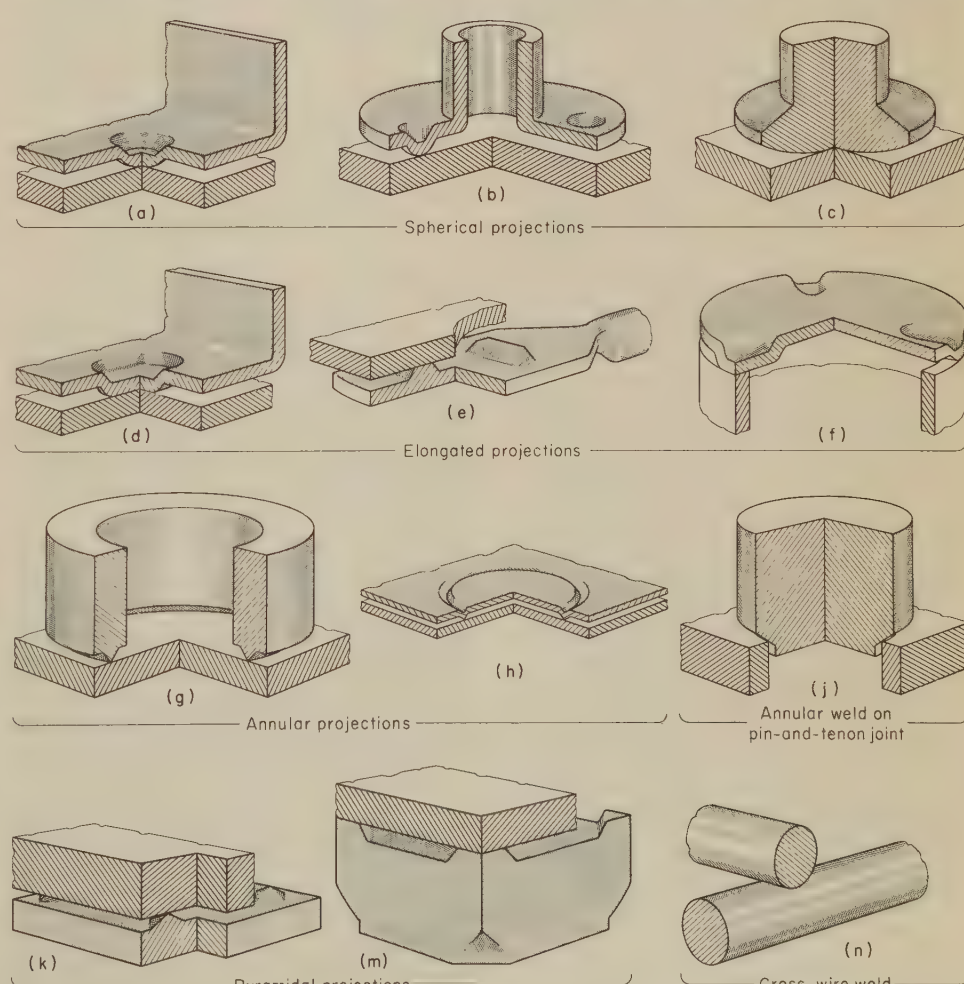


Fig. 11. Variations on basic types of projections. See text for discussion of application.

follow-up. The short time required to heat a spherical projection to welding temperature and the relatively small height of spherical projections necessitate extremely fast follow-up of the electrode. However, electrode force need not be as high as for welding thicker work metal. Lack of rigidity in the projection and lack of resistance to collapse before the welding current has been applied require careful adjustment of the initial electrode force.

The annular projection shown in the illustration with Table 3 has greater resistance to cold collapse, and can be used in place of a spherical projection for welding thin sheet metal parts. The welding conditions listed in Table 3 are for welding 1010 steel 0.0105 and 0.0179 in. thick using annular projections. The 6-cycle (0.1-sec) weld time shown allows latitude in selection of electrode force and welding current.

Intermediate-thickness workpieces, from 0.022 to 0.135 in. thick, are the most adaptable to projection welding. Workpieces up to 0.135 in. thick are more easily welded and more commonly used than workpieces greater than 0.135 in. in thickness. Table 1 gives recommended conditions for welding low-carbon and low-alloy steel in thicknesses up to 0.125 in. with one projection. For multiple-projection welding, electrode force and welding current are increased in direct proportion to the number of projections.

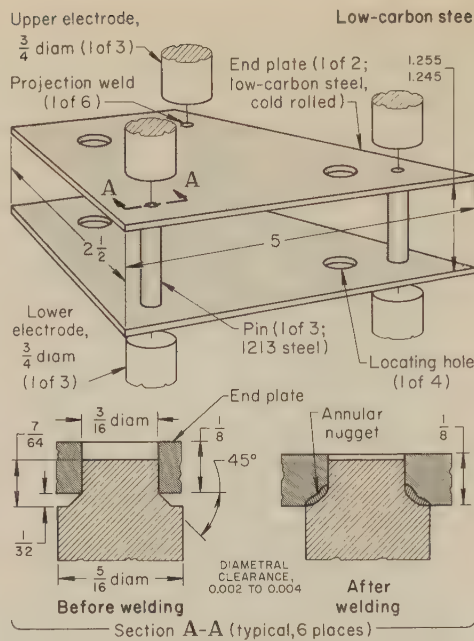
Thick Workpieces. Projection welding of workpieces 0.136 to 0.250 in. thick is limited because of the large equipment and the high power required. Welding in this thickness range generally results in an increase in weld porosity, an increase in sheet separation because of the difficulty of obtaining complete projection collapse, and an increase in expulsion of metal because the large machines needed usually have sluggish follow-up.

Weld porosity is difficult to eliminate, but can be minimized by using a lower electrode force during welding to reduce the current required and to prevent premature projection collapse, and by applying forge force immediately after the weld time. The use of pulsation timing may also be helpful.

Expulsion of metal resulting from sluggish ram movement can be compensated for by using upslope control to increase the current gradually during weld time. This procedure decreases the rate of follow-up needed to maintain proper welding force.

Sheet separation is minimized through the use of either forge force or a recessed type of projection. The illustration with Table 4 shows a recessed projection, and the table gives dimensions for recessed projections in low-carbon steel 0.123 to 0.245 in. thick. The tools needed for making recessed projections have short life, and because this type of projection is coined and not embossed, press capacity for making a projection in 0.250-in.-thick low-carbon steel must be about 30 tons.

Recessed projections limit weld strength. The metal that flows into the recess does not contribute appreciably to weld strength, but the recess permits complete collapse of the projection at lower electrode forces than are



Equipment Details

Welding machine	Semiautomatic press type
Rating at 50% duty cycle	200 kva
Current, max	75,000 amp
Transformer	Four-tap series-parallel
Electrodes	¾-in.-diam RWMA class 2
Heat control	Phase shift

Welding Conditions

Welding current, approx	70,000 amp
Transformer tap setting	Parallel, No. 4
Heat-control setting	90%
Electrode force, total	3500 lb
Squeeze time	30 cycles
Weld time	20 cycles
Hold time	30 cycles
Production per hour	42 assemblies (252 welds)

Fig. 12. Platen-frame assembly projection welded using a pin-and-tenon joint to allow efficient handling in high production and to minimize penetration in free-machining 1213 steel pins (Example 396)

needed for collapsing conventional spherical projections.

Suggested projection size and welding conditions for projection welding two equal thicknesses of low-carbon steel from 0.153 to 0.245 in. thick using normal-size and small-size projections are given in Table 5. Dimensions given for normal-size projections are slightly different from those given in Table 2. The small-size projections can be used when two or more are needed, or to reduce the welding-machine size and the power requirements.

A special technique that is sometimes used in low-production projection welding of thick work metal is to insert a slug of metal between two flat workpieces to serve as a projection, thus avoiding the difficulties and cost of producing a conventional projection.

Workpieces of unequal thickness are projection welded about as often as are workpieces of equal thickness. Projections can be placed in either workpiece, although weld properties are less affected by variations in welding conditions if the projections are formed in the thicker component; this was done in Example 405, where the two components had a thickness ratio of 3 to 1. In welding workpieces in thickness ratios greater than 3 to 1, it may be more practical to place the projection in the thinner component, as was done for a clutch mount in Example 392.

The conditions listed in Tables 1 and 2 can be used for welding workpieces of unequal thickness. The welding current and weld time may have to be increased to obtain a sufficiently large nugget diameter and adequate penetration, and to minimize sheet separation. The added energy increases both the diameter of the nugget and the shear strength of the joint.

Projection Welding of Bar Stock to Sheet Metal

Projection welding of bar stock to sheet metal can be done easily if the parts and projections are correctly designed. Fasteners such as pins, studs and nuts are welded to sheet metal using spherical (Fig. 11a, b and c), pyramidal (Fig. 11k and m) and annular (Fig. 11g and h) projections, as an alternative to attaching them by stud welding or percussion welding.

Provision must be made for holding the component made of bar stock so that it can be welded at the correct angle with the mating part and so that the current path is as short as possible. Flow of current through a long slender shaft should be avoided, when possible, by applying the current to the shaft near the weld area.

In Example 407, in which a headed stud was welded to a sheet metal housing, an annular projection was formed on the underside of the head, and the shank of the stud was passed through a hole in the housing. Thus the upper electrode contacted the top of the head and provided a short path for the welding current.

In another type of joint design, as shown in Fig. 11(j), a tenon on the end of the pin acts as a pilot for inserting the pin into the hole in the sheet metal part, and an adjoining conical tapered section makes annular contact with the sharp edge of the hole, which localizes the current and heating. This joint design, which was used in Examples 396 and 397, facilitates fixturing and assembly, and is well suited to high-production welding in semiautomatic and automatic resistance welding machines.

In Example 396, three pins were projection welded at both ends to two platens 1.25 in. apart, making six welds at once, with the electrodes directly above and below each pin. In Example 397, in which a shaft was welded to a plate, a short current path was provided by resting the upper electrode on the plate and clamping the lower electrode to the shaft below the plate.

Besides being well suited to high-production welding, this type of joint permits the use of free-machining steel in the pin or shaft, because it allows close control of heating and a minimum of penetration into the pin or shaft, thus avoiding weakness and porosity that would result from segregation of sulfur or phosphorus in the free-machining steel during welding.

The use of this type of joint design (Fig. 11j) to allow high-production welding of free-machining steel is described in the next two examples.

Example 396. Use of Pin-and-Tenon Joint With a 45° Bevel To Allow High-Production Projection Welding of Free-Machining Steel to Low-Carbon Steel (Fig. 12)

The platen-frame assembly shown in Fig. 12 consisted of two end plates made of cold rolled low-carbon steel and three 5/16-in.-diam separating pins made of free-machining 1213 steel. Although 1213 steel generally is unsuitable for resistance welding, it was used for the pins because most of the molten metal for the welds was provided by the low-carbon steel plates, and because machining time was about half that for non-free-machining steel.

A 45° bevel on the pin between the 3/16-in.-diam tenon and the 5/16-in.-diam body of the pin was used to contact the sharp edge of the hole in the end plate, and thus the sharp edge acted as a projection and was melted to make the weld (see section A-A in Fig. 12). Penetration into the free-machining steel, inclusions in the weld nugget, and dilution of the low-carbon steel, which would destroy the bonding properties of the weld metal, were minimized.

The six welds were made simultaneously, using the equipment and welding conditions given in the table with Fig. 12. To make the six welds simultaneously, the lower electrodes were fixed in position while the vertical positions of the upper electrodes were hydraulically equalized to compensate for variations in pin length and electrode wear. The welding fixture included locating pins that fitted tightly into the two pairs of locating holes shown in Fig. 12 to maintain alignment of the two platens during welding.

One weldment from every hundred was checked by the operator in a go/no-go gage for dimensional accuracy. One of each 300 weldments was tested to destruction. Each of the broken welds was required to show evidence of torn metal.

Previously, these platen-frame assemblies had been joined by riveting over the ends of the pins. Riveting required 12.98 hr per 100 assemblies, whereas projection welding required only 2.38 hr. Because annual production was 30,000 assemblies, the change to projection welding resulted in a saving of 3180 hr per year.

Projection welding required the purchase of a new resistance welding machine ($10,000) and welding dies ($3000), but these expenditures were outweighed by the saving in time and also by a saving in material. The saving in material was obtained because the added strength and rigidity of the projection welded assembly allowed a reduction in the number of pins per assembly from four to three.

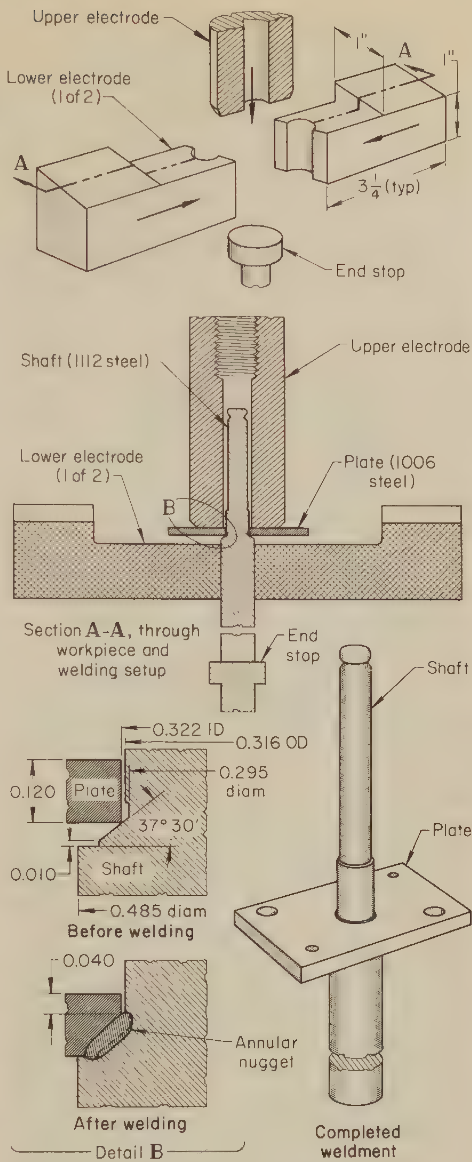
Example 397. High-Speed Automatic Projection Welding of a Free-Machining Steel Shaft to a 1006 Steel Plate, Using a Pin-and-Tenon Joint With a 37° Bevel (Fig. 13)

The plate-to-shaft assembly shown in Fig. 13 was made in an automatic resistance welding machine equipped with a four-station indexing turntable. Before welding, as shown in detail B in Fig. 13, the edge of the hole in the plate rested on the conical land on the shaft.

In the first station, the large-diameter end of the shaft was placed in the lower electrode; in the second station, the plate was dropped onto the shaft; in the third station, the upper electrode was lowered to contact the plate, and the joint was welded; and in the fourth station, the weldment was ejected.

As shown in detail B in Fig. 13, an annular weld nugget was formed by fusion of metal from the lower edge of the hole and from the contacting region of the beveled portion of the shaft. Also, plastic metal was forced into the 0.295-in.-diam recess in the shaft, reinforcing the joint.

As shown in Fig. 13, the upper electrode surrounded the small-diameter end of the shaft and bore against the plate when in welding position, and two lower electrodes



Equipment Details

Welding machine	Automatic, with four-station indexing turntable
Rating at 50% duty cycle	100 kva
Current, max	65,000 amp
Heat control	Eight-tap transformer and phase shift
Electrode material	RWMA class 3
Electrode force, max	2300 lb, approx

Welding Conditions

Welding current, approx	45,000 amp
Welding voltage	7.8 v
Electrode force	1550 lb
Squeeze time (including machine delay time)	99 cycles
Weld time	6 cycles
Hold time	11 cycles
Production per hour	666 assemblies

Fig. 13. Free-machining steel shaft and steel plate that were automatically projection welded together in mass production, producing an annular weld at a pin-and-tenon joint (Example 397)

centered and clamped the shaft. An end stop kept the shaft from moving downward under the force of the upper electrode.

Originally, an angle of 26° was specified for the conical land on the shaft, but with this angle satisfactory welds were not always produced. Use of a 37½° cone angle and the welding conditions given in the table with Fig. 13 produced sound welds. A few faulty welds were caused by a short between the shaft and the upper electrode.

Weldments were tested during setup, to establish the welding conditions, and tests were made after welding each production run of 500 assemblies. The tests consisted of placing the small end of the shaft on an anvil and striking the ends of the plate until they were bent 30°. Welds that did not break were considered satisfactory. This test was preferred to a tensile-load test in which the plate was pushed off the shaft, because the tensile-load test could be passed by weldments that were pressure bonded but that lacked adequate fusion to withstand fatigue loading.

After each 15,000 welds, the electrodes were removed from the machine and dressed by grinding. The two lower electrodes required grinding in sets. Equipment details and welding conditions are given in the table with Fig. 13.

Projection welding of powder metallurgy parts (sintered compacts) is similar to projection welding of free-machining steel in that penetration into the sintered metal must be kept to a minimum. In joining sintered iron to 1010 steel in Example 402, this was accomplished by producing an annular weld nugget at the contact line between the sharp edge of a hole in the steel and the beveled surface of a specially formed truncated conical boss on the sintered iron.

Projection Welding of Tube to Sheet Metal

Standard tube and pipe, and other parts of cylindrical shape, can be projection welded to sheet metal at the sidewall or at the end of the tube. The sidewall of a tube can be welded to sheet metal using elongated projections embossed in the sheet metal component, as shown in Fig. 14. The elongated projection provides localized con-

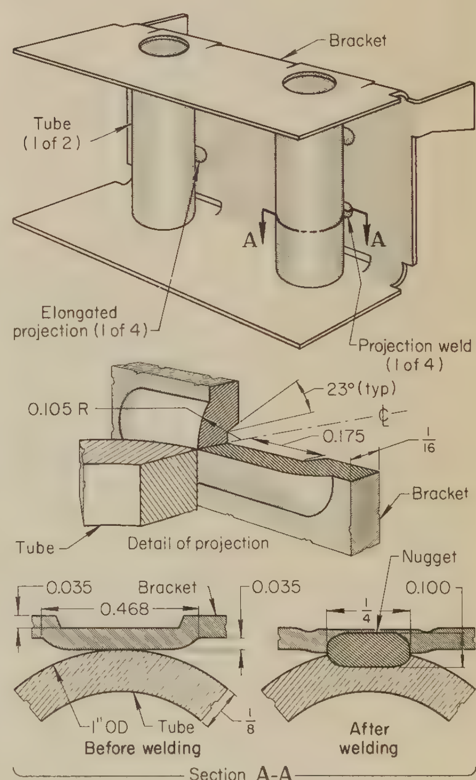


Fig. 14. Projection welding of the sidewalls of tubes to a sheet metal bracket using elongated projections formed in the sheet

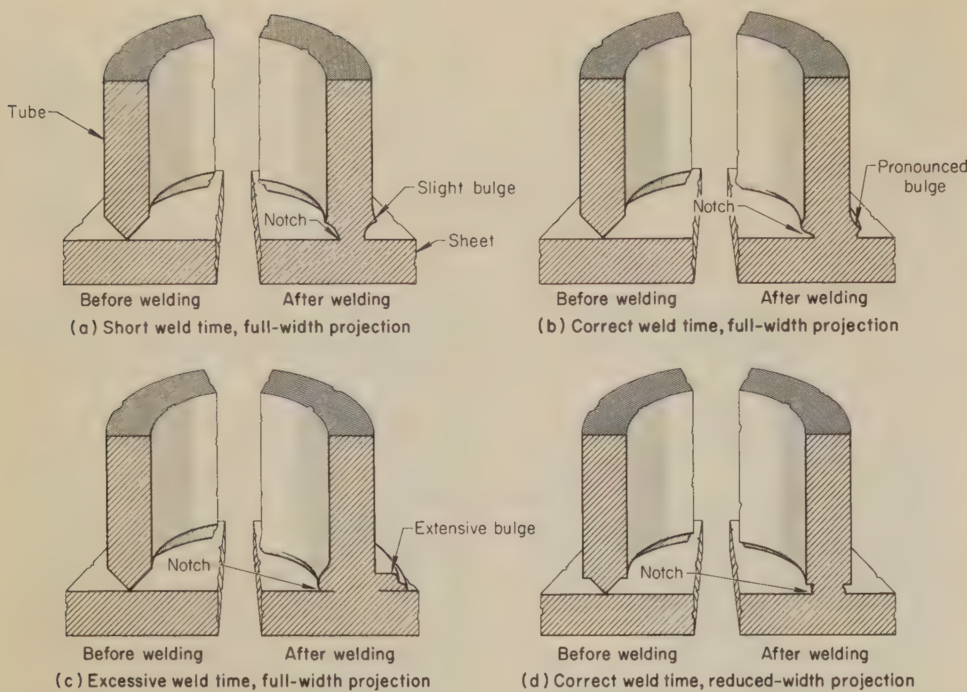


Fig. 15. Effects of weld time and width of annular projection on appearance of tube-to-sheet welds (J. J. Riley and J. F. Harris, "Annular Projection Welding of Tubular Sections to Low-Carbon Steel Sheet", *Welding Journal*, July 1966; reprinted as RWMA Bulletin 35)

tact with the tube and requires less accurate positioning than does a spherical projection.

The end of a tube can be welded to sheet metal by the use of annular projections, which results in uniform, liquid-tight welds. Annular projections are easily machined on tube ends.

Projection Shape. Strength and final appearance of tube-to-sheet welds depend principally on projection shape and welding conditions. The recommended projection, referred to as a full-width projection, has a 90° included angle machined to intersect both the outside and inside surfaces of the tube, and a base width equal to wall thickness (Fig. 15a). A reduced-width projection, which has a base width less than wall thickness (Fig. 15d and Fig. 11g), can be used to minimize deformation of the tube wall.

The appearances of tube-to-sheet welds made with full-width annular projections using short, correct and excessive weld times are shown in Fig. 15(a), (b) and (c). The appearance of a weld made with the correct weld time and a reduced-width projection is shown in Fig. 15(d).

Figure 15(a) illustrates the use of a short weld time to avoid full collapse of the projection. During welding, the outside diameter of the tube is slightly increased at the top of the projection.

With a longer weld time, width of the weld produced is approximately equal to the wall thickness of the tube. As shown in Fig. 15(b), the outside diameter of the tube is increased, and the inside diameter is decreased, at the top of the projection.

The appearance of a weld made with excessive weld time is shown in Fig. 15(c). Flow of the weld metal is restricted in the vertical direction by the clamping electrode, and a well-defined horizontal weld-metal surface is formed around the outside of the tube. Bulging of the weld metal inside the tube is uniform and blends into the tube wall. The weld metal that bulges beyond the original inner and outer tube walls is not subjected to enough electrode force to become properly bonded, and therefore does not add to weld strength.

The reduced-width projection shown in Fig. 15(d) can be used to minimize deformation of the tube wall. The weld width is less than the thickness of the tube wall, and the shape of the weld metal generally is symmetrical about the initial-contact circle.

Regardless of weld time, initial joint preparation or width of the projection, a notch is visible at the intersection of the inner tube wall and the surface of the mating workpiece (see Fig. 15). Unless weld time is excessive, a notch is visible also at the intersection of the outer tube wall and the mating workpiece. There is always some bulging of the weld metal beyond the original inner and outer tube walls when intended weld width approaches wall thickness.

Heat Balance. The two components of a tube-to-sheet joint in which an annular projection is used have different configurations, which can cause unbalanced heating. The welding current flowing through the tube wall near the weld interface heats the tube wall enough to prevent heat loss to this area from the weld interface during welding. However, as the current leaves the projection and enters the sheet, heat starts to flow away from the weld area into the surrounding cold metal. Heat flow in the sheet is limited by its thickness and thermal conductivity. In general, heat loss by thermal conduction is not a major problem in projection welding of low-carbon steel using annular projections.

As sheet thickness increases beyond tube-wall thickness, the assembly becomes increasingly difficult to weld because additional time or welding current is needed to bring the contacting surfaces to welding temperature. The tube wall behind the weld interface collapses more readily because of a large heat-affected zone, and metal expulsion increases during welding.

Electrode Design. The electrodes that clamp the tube should be designed to make contact at two areas — one near the weld for electrical contact and the other near the top of the tube for alignment. This arrangement localizes the welding current near the weld and helps to hold the tube perpendicular to the sheet so that the apex of the projection is in uniform contact with the sheet. Clamping force causes the tube to conform to the electrode shape so that current density is uniform at the electrode contact surface.

If the welding current is unevenly distributed around the tube, unequal heating can occur at the weld interface. If localized melting occurs on the tube near the edge of the electrode, the electrode-contact surface must be enlarged or made uniform by remachining the electrode or the tube. Other alternatives are increasing the clamping pressure, or removing scale, varnish or other foreign material from the surface of the tube, to reduce contact resistance.

The initial extension of the tube from the clamping electrode should be about twice the wall thickness. Longer extensions may cause more heating and upsetting during welding, which can decrease the weld pressure because of a larger weld interface.

Weld Strength. Tube-to-sheet weldments, when tested to destruction, can fail in the tube wall, in the weld, or by tearing a slug of metal from the sheet around the weld circumference. Those assemblies in which the sheet thickness is equal to or greater than tube-wall thickness can be expected to fail at the interface because the sound weld area is smaller than the cross-sectional area of the tube.

The tensile strength of properly welded joints made with reduced-width projections is nearly the same as that of joints made with full-width projections, whether failure in testing is at the interface or in the base metal.

Cross-Wire Welding

Resistance welding of crossed wires, generally in a grid arrangement in which a number of parallel wires are welded at right angles to one or more other wires, is a form of projection welding. Cross-wire products can be welded in a press-type resistance welding machine using a welding die or special individual electrodes.

If the wires are close together, a seam welding machine can be used. The wires are assembled in a fixture and the current-carrying member of the fixture can be placed on a lower platen or can contact the lower electrode wheel. The upper electrode wheel contacts the upper tier of crossed wires. Welding current flows continuously and weld time for each cross-wire weld is determined by the speed of the electrode wheels.

Resistance between electrodes and work metal should be uniformly low to minimize power loss and surface damage, but resistance between faying surfaces should be uniformly high to concentrate heat for welding. Grooved electrodes provide low contact resistance between electrode and work metal. The point contact resulting from the shape of the crossed wires provides high resistance at the work-metal interface. Bars that are square, rectangular or hexagonal in cross section can be cross-wire welded if positioned so that the joint is formed by edges, rather than by flat surfaces.

Wires or bars from 0.020 to ½ in. in diameter have been cross-wire welded. The upper and lower limits of wire diameter are governed mainly by the capability of accurately controlling the welding current and the electrode force for small-diameter wires, or of providing adequate current and force for large-diameter wires.

Metals Welded. Low-carbon steel, stainless steel, copper, and nickel-base alloys such as Monel are among the metals commonly cross-wire welded. Table 6 gives recommended conditions for welding low-carbon steel wire.

Type 304 stainless steel requires the same weld time, 60% of the current and 2½ times as much electrode force as is needed for welding low-carbon steel (see page 464 and Table 7 in the article on Resistance Welding of Stainless Steel), whereas Monel requires the same weld time and current but twice the electrode force.

Cross-wire welding of galvanized and cadmium-plated wire can be done, but destroys the plating surrounding the weld. Also, welding of cadmium-plated metal requires special safety precautions because of the high toxicity of cadmium vapors.

Electrode force needed for a cross-wire weld depends on wire diameter, setdown requirements (the amount the wires are to be embedded into each other), desired appearance and required weld strength.

The values of electrode force, weld time and current given in Table 6 will produce strong welds with good appearance. Lower forces can be used with longer weld times, but weld strength may decrease.

Weld time depends mainly on wire diameter. Consistent results are obtained by using synchronous timing control.

Welding current depends on wire diameter, setdown requirements and weld time. The welding current selected should be slightly less than that resulting in expulsion of hot metal.

Electrode Design. Flat electrodes or dies can be used for cross-wire welding, but electrodes or dies that are grooved to fit the diameter of the wires provide better contact between electrode and workpiece. A suitably grooved electrode reduces contact resistance at the electrode-wire interface and minimizes arcing and excessive marking of the wires. Alignment is critical for producing consistent welds.

Examples of Practice. In the following example, resistance cross-wire welding with grooved electrode faces partly replaced shielded metal-arc welding in producing cage assemblies.

Example 398. Partial Change From Shielded Metal-Arc to Resistance Cross-Wire Welding To Reduce Production Time and Costs (Fig. 16)

The cage assembly shown in Fig. 16 was one of three put together to form a protective guard for a twister winder used in the textile industry for making thread. The components, made from $\frac{5}{16}$-in.-diam 1118 steel bar (except for the base ring, which was made from ¼-by-½-in. 1018 steel bar), were cut to length, shaped and fitted.

Originally, the cut, formed and fitted bars were joined at all contact points by shielded metal-arc welding. The resulting welds were then ground smooth. When arc welding was replaced by resistance cross-wire welding for making all welds not involving the base ring, rejects were eliminated, weld strength was adequate, appearance was improved, and both production time and costs were reduced.

In the improved method, the ends of the two upright members, one end of each of the two diagonal braces, and three brackets (not shown in Fig. 16) were shielded metal-arc welded to the base ring while the components were clamped in a welding fixture. The assembly was then placed in an aluminum alloy fixture, where 15 resistance cross-wire welds were made, joining the three horizontal rings to the diagonal braces and to the upright members.

An aluminum alloy was used for the fixture material because aluminum is light and easily handled, and because it is nonmagnetic and thus has no effect on resistance and reactance, regardless of the amount introduced in the throat of the machine.

The electrodes for resistance welding were notch contoured, as illustrated in Fig. 16. The cage bars were placed in these notches and were forced together to make the weld. The notches were shallow enough to avoid contact and short circuiting between the electrode and the opposing bar.

When all welds were made by shielded metal-arc welding, the cost of producing a three-cage assembly was $169.38. When resistance welding was used for joining the horizontal rings to the diagonal braces and the upright members, cost was reduced to $138.84, for a saving of $30.54. Also, production time for a three-cage assembly was reduced by 2½ hr, because resistance welding was faster than shielded metal-arc welding, and because postweld grinding was not needed to clean the assembly.

All joints were inspected visually for weld soundness. The three cage assemblies, all made in much the same manner, were joined with bolts and hinge pins to form the completed protective guard, which was then painted.

Equipment details and welding conditions for cross-wire resistance welding are given in the table with Fig. 16.

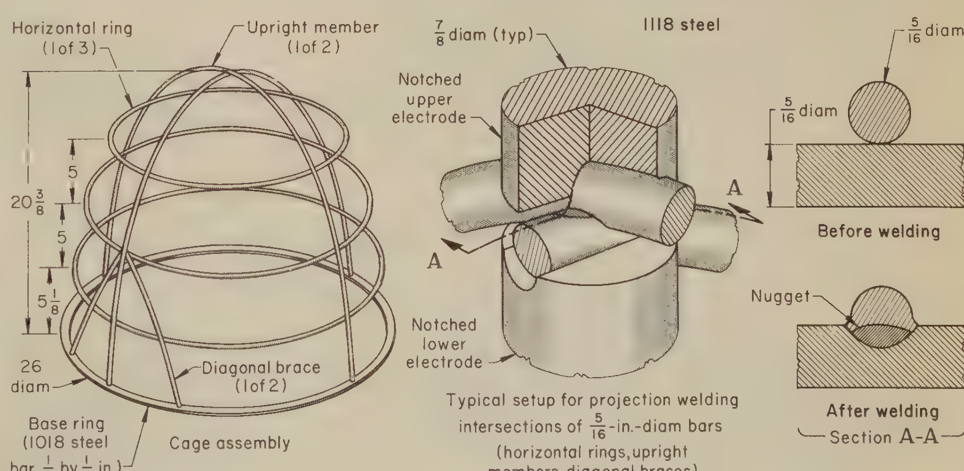
Techniques have been developed for welding crossed wires that have a plastic coating or are separated by a thin layer of plastic. During the squeeze time, sufficient electrode force is applied to cause the wires to penetrate the plastic material and make electrical contact. Sometimes, the penetration can be facilitated by preheating the electrodes by the use of a special heating circuit; in the example that follows, no preheating was needed.

Example 399. Projection Welding of Crossed Wires Through a Sheet of Plastic To Produce a Circuit Board (Fig. 17)

The circuit board shown in Fig. 17 was produced by projection welding crossed 0.020-in.-diam Nickel 200 wires that were separated by a sheet of Teflon or similar plastic 0.010 in. thick. A specially designed 5-kva spot welding machine equipped with a heat-programed timer was used for making the welds through the plastic sheet. Optimum welding current and electrode force were determined experimentally. Both upper and lower electrodes were made of RWMA class 3 material.

The electrode force of 23 lb exerted on each pair of crossed wires corresponded to a local pressure of about 7500 psi, which was sufficient to cause the wires to penetrate the layer of plastic and make electrical contact. Other plastic materials that were found to have sufficiently good cold flow characteristics for use in this application included polyethylene.

The transverse and longitudinal wires were assembled in a grid wireholding fixture. Spacing of parallel wires in both directions was 0.100 ± 0.005 in. Some welds were made to hold parallelism of wires, and others were made to stop off unneeded wires. The portion of a wire not needed in the circuit was removed by piercing a hole through the plastic sheet at the wire-cutoff



Welding machine ....Three-phase manually operated resistance	Electrode force ....700 lb
Rating at 50% duty cycle ....100 or 150 kva	Squeeze time ....25 cycles
Electrodes ....⅞-in.-diam RWMA class 2	Weld time ....4 cycles
Welding current ....1000 amp	Hold time ....18 cycles
	Production rate ....2 cages per hour(a)

(a) Includes 15 cross-wire resistance welds on $\frac{5}{16}$-in.-diam 1118 steel bars and 8 shielded metal-arc welds on ¼-by-½-in. 1018 steel base ring for each cage.

Fig. 16. Textile-machine cage for which partial change from shielded metal-arc welding to cross-wire resistance (projection) welding under conditions given in table reduced production time and costs (Example 398)

point (see detail A at lower left in Fig. 17). The welded circuit board was later encapsulated in plastic to maintain dimensional tolerances and strength.

Parallelism and perpendicularity were measured mechanically; wire positions were held to ±0.005 in. Weld strength was tested by making sample cross-wire welds and pulling the welded crossed wires into a straight line. Production rate was 10,000 cross-wire welds in 8 hr (including testing). Total cost, including testing, was $0.32 per 100 welds plus $0.33 per circuit for setup time.

Methods of controlling the quality of cross-wire welds are described in Examples 403 and 404. In Example 403, wire tensile strength was closely controlled to ensure repeatability of cross-wire welds. In Example 404, wire-inductance tests were used, in place of destructive pull tests, to save time in determining weldability.

Projection Welding of Dissimilar Metals

Metals differing in thermal and electrical conductivity can be projection welded, provided the surfaces being welded are brought to welding temperature simultaneously. This usually can be done by forming the projection in the higher-conductivity metal, by using a low-conductivity copper-tungsten electrode (class 10, 11 or 12) in contact with the higher-conductivity metal, or by combining these two conditions.

If the conductivities of the components are not widely different, a satisfactory heat balance usually can be obtained without using electrodes made of different materials. Differences in thermal and electrical conductivity between two metals ordinarily are closely parallel; the more conductive metal will generate less resistive heat because of its higher electrical conductivity and dissipate heat more rapidly because of its higher thermal conductivity.

In the following example, in which type 430 stainless steel was welded to galvanized steel, the projections were formed on the galvanized steel, which has higher thermal and electrical conductivity than the stainless steel.

Example 400. Change From Spot Welding to Projection Welding of Type 430 Stainless Steel to Galvanized Steel To Reduce Electrode Pickup and Rejection Rate (Fig. 18)

The lower-track assembly for a sliding mirror door in a bathroom cabinet was made by joining two track channels made of type 430 stainless steel to a larger track-support channel made of galvanized steel, using four projection welds (Fig. 18).

Originally, the welds were made one at a time by spot welding. The track channels were positioned manually on the support channel, and two spot welds, one in each track channel, were made in succession at one end of the assembly. The assembly was then turned and the other end was similarly welded. The upper and lower spot welding electrodes had ⅛-in.-diam faces.

Production rate for spot welding was 123 assemblies per hour, and about 10% of the welded assemblies were rejected because of weld breakage. A major factor contributing to weld breakage was pitting of the lower-electrode face, which occurred because the copper electrode became alloyed with zinc from the surface of the support channel. This zinc pickup caused changes in the contact resistance (and therefore, poor welds) and necessitated frequent dressings of the lower electrode. Dressing, which was done manually with a file, produced a nonuniform face contour, which also caused variation in weld quality. Rewelding of faulty assemblies was expensive because of rework itself and need for close inspection imposed by the high rejection rate.

To improve weld quality, the joining method was changed to projection welding. Because galvanized steel has higher thermal and electrical conductivity than type 430 stainless steel, the spherical projections were formed on the support channel, as shown in Fig. 18, permitting a reduction in electrode force and current density on the external zinc-coated surface.

The change to projection welding in the setup shown in Fig. 18 reduced zinc pickup by the electrode while allowing the use of sufficient electrode force to ensure consistently sound welds. Frequent removal of zinc from the lower electrode was not needed, and rejection rate was reduced from 10% to 0.1%, or by a factor of 100.

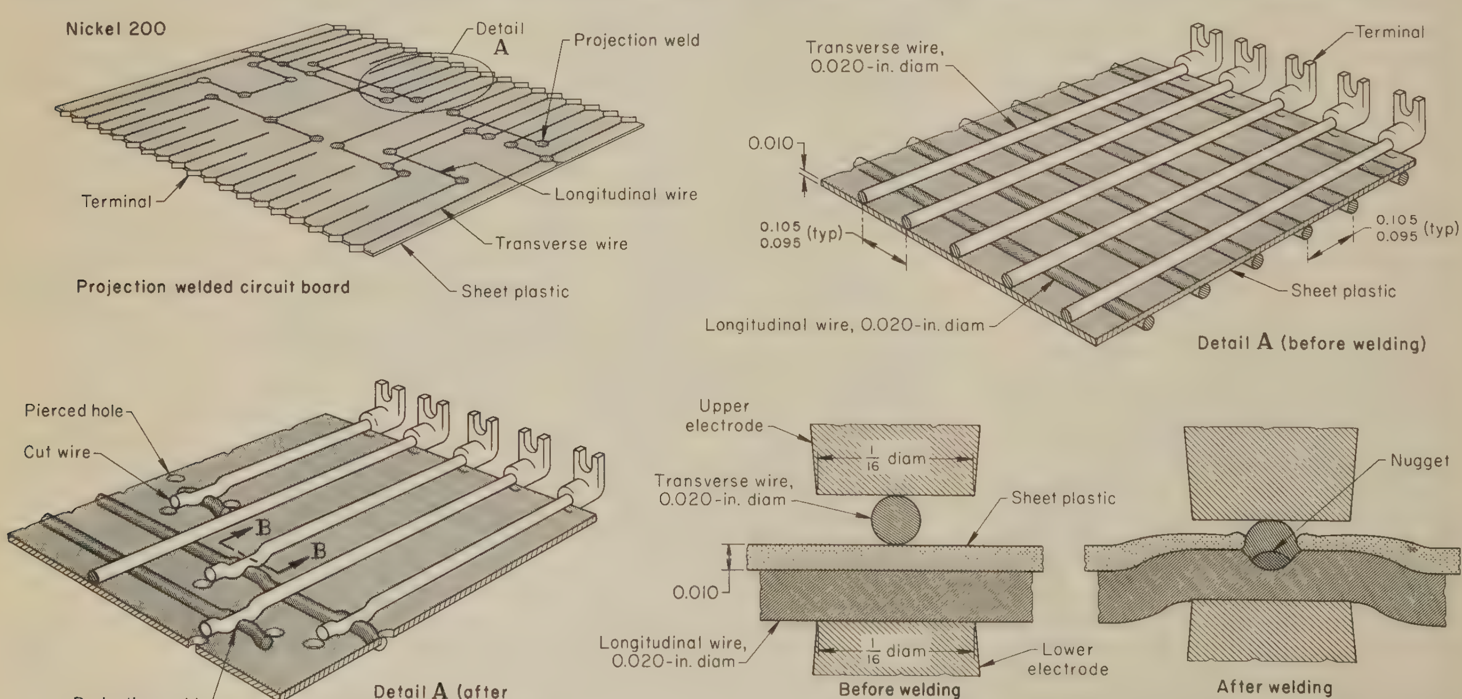
The upper and lower electrodes used for projection welding had large, flat contact faces, and were water cooled to dissipate heat generated at the welds. Gage blocks were attached to the lower electrode for automatic positioning of the three channels for welding. The two projection welds at each end of the track assembly were made simultaneously.

Production rate was increased from 123 to 173 assemblies per operator per hour, and welding cost was reduced from $2.60 to $1.90 per hundred assemblies.

Projection Welding of Coated Steel

Low-carbon steels coated with zinc, lead-tin or aluminum are projection welded in large quantities. Low-carbon steels with thin coatings of copper, tin, nickel, chromium or cadmium are easily projection welded using a welding current generally about 10% greater than that used for welding bare low-carbon steel of equal thickness.

Schedules for projection welding of galvanized low-carbon steel are given in Table 7. These schedules apply for galvanized steel with a commercial coating weight (1.25 oz of zinc per square foot of sheet). Zinc-coated steel having thinner coatings is usually welded using the conditions given for



Welds were made in a specially designed 5-kva resistance spot welding machine equipped with a heat-programed timer, using direct current, square-wave pulse. Electrodes were of RWMA class 3 material, 2 in. long, with type A (pointed) 1/16-in.-diam tips and ⅜-in. diam bodies. Electrode force was 23 lb, equivalent to a pressure of about 7500 psi at cross-wire intersections, sufficient to cause penetration of the plastic sheet by the wires and to establish electrical contact between the wires. Weld time was 5 millisec. Production rate, including testing, 10,000 welds per 8 hr.

Fig. 17. Circuit board that was produced by projection welding of crossed wires separated by a 0.010-in.-thick plastic sheet (Example 399)

bare low-carbon steel in Table 1, or conditions intermediate between those in Tables 1 and 7.

Electrode pickup is common in projection welding of steel coated with aluminum, tin or cadmium because these metals readily alloy with copper-base electrodes. Frequent cleaning and re-dressing of the electrodes are necessary to remove any pickup on the electrode faces. Electrode pickup occurs also in projection welding of zinc-coated steel, but although there is some alloying between zinc coating and copper-base electrodes, most of this pickup results from "soldering" of the zinc to the electrode face, which necessitates frequent cleaning. Copper, nickel and chromium do not diffuse readily into copper-base electrodes, and pickup is less troublesome in projection welding steel coated with these metals.

Generally, less electrode pickup occurs in projection welding than in spot welding of coated steel because the initial heating is concentrated at the tip of the projection, and current density is lower on projection welding electrodes than on spot welding electrodes. For instance, in Example 400, in which galvanized steel was welded to type 430 stainless steel, changing from spot welding to projection welding allowed reduction of electrode force and current density, and thus reduced deterioration of the electrode face.

Electrode pickup in projection welding of coated low-carbon steel can be reduced if careful attention is given to joint design, electrode design and adjustment of hold time.

The joint should be designed so that the metal coating (particularly zinc and tin) can be burned or extruded from between the surfaces to allow formation of a weld nugget in the base metal. Size and shape of the electrode face should be such that heating is adequate but current density at the electrode face is low.

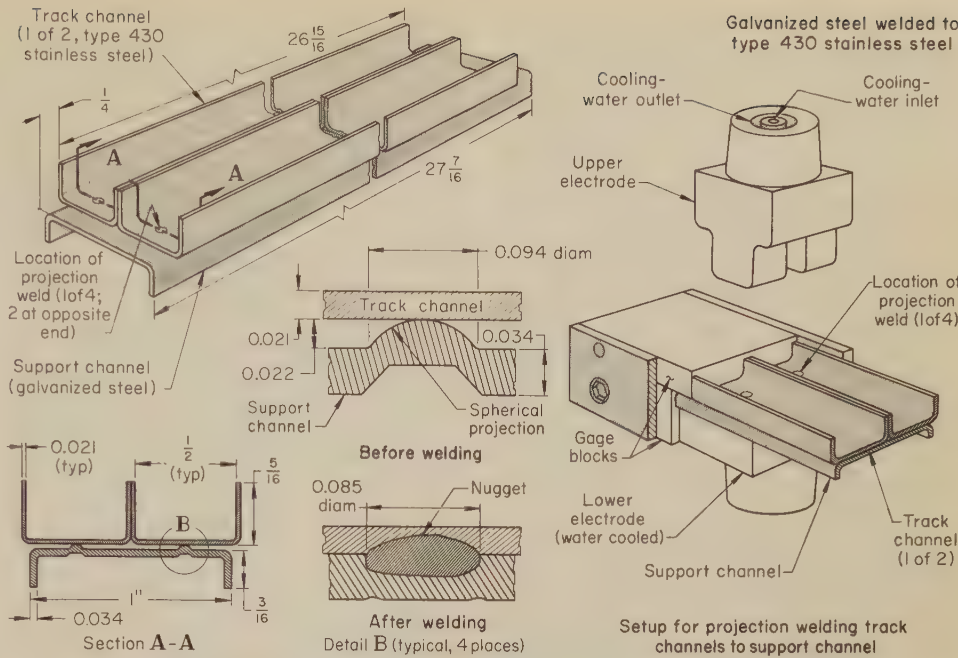
The hold time should be long enough to permit the molten coating metal (particularly zinc and tin) at the contacting surfaces near the weld nugget to solidify, thus reinforcing the weld.

Example of Practice. In the following example, distortion during spot welding of a handle to a trash-can cover, both made of galvanized steel, resulted in an excessive percentage of weak joints between layers of zinc that had melted and resolidified. Changing to projection welding reduced the occurrence of faulty welds.

Example 401. Change From Spot Welding to Multiple-Projection Welding of Galvanized Steel To Avoid a Fit-up Problem That Resulted in Weak Solder-Type Joints (Fig. 19)

The trash-can cover and handle shown in Fig. 19 were joined by four projection welds that were made simultaneously. Both the handle and the cover were made of galvanized steel.

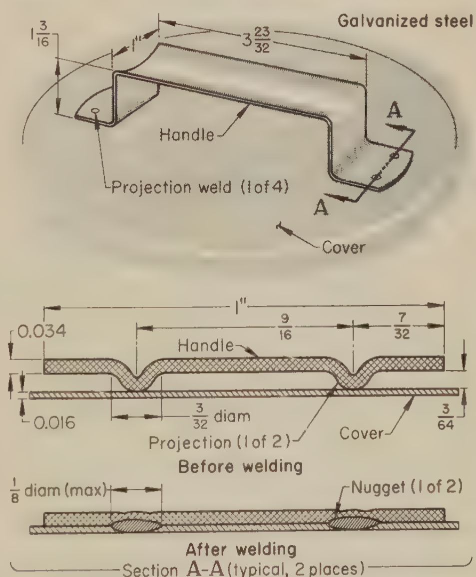
Originally, the handle was joined to the cover with four spot welds that were made one at a time. The cover was placed in a fixture in the welding machine, the handle was manually positioned, and two spot welds were made in one end of the handle. Then the cover was indexed and two spot welds were made in the other end of the handle. About 8% of the assemblies joined by this method had poor welds and required reworking.



Projection welding was done on a press-type machine with electronic controls and a transformer rated (at 50% duty cycle) at 30 kva, using special-shape RWMA class 3 electrodes; production rate was 173 assemblies (692 welds) per hour.

Fig. 18. Lower-track assembly for a sliding door, for which change from spot welding to projection welding increased production and reduced rejections and costs (Example 400)

The high rate of weld failure was caused mainly by poor fit-up of the handle and cover for the second pair of spot welds. When the first end of the handle was



Conditions for Projection Welding

Welding machine	Press type, precision
Electrode material	RWMA class 2
Heat-control setting	91%
Squeeze time	15 cycles
Weld time	7 cycles
Hold time	9 cycles
Production per hour:	
Projection welds	1296 (324 assemblies)
Spot welds(a)	960 (240 assemblies)
Rejection rate:	
Projection welding	0.08%
Spot welding(a)	8%

(a) With a manual, foot-operated welding machine and RWMA class 2 electrodes

Fig. 19. Galvanized handle-and-cover assembly for which change from spot welding to multiple-projection welding increased production by 35% and decreased rejections by 99% (Example 401)

welded, the other end usually gapped away from the cover, producing a spring action that reduced the effective electrode pressure when the second pair of welds was made. With this reduced pressure, contact was insufficient to burn the zinc coating from between the surfaces, and weak solder-type joints were made instead of sound spot welds in the base metal. Also, excessive wear of the upper electrode caused variations in nugget size and weld quality.

When the process was changed to multiple-projection welding using a press-type machine and a welding die, rejection rate was reduced to 0.08%, and production rate was increased from 240 to 324 covers per hour.

In the improved method, the welding die located the two workpieces, and all four projection welds were made simultaneously. The welds were inspected visually for size and could not exceed ⅛ in. in diameter.

In both methods, ten assemblies were randomly selected from each production lot and were tested for weld strength by striking the ends of the handles near the welds with a 4-oz weight swung from a height of approximately 18 in.

The electrodes used in spot welding were dressed manually by the operator as needed. The welding-die inserts used in projection welding required no hand dressing, but were removed for machine dressing at regular intervals. Conditions for projection welding are given in the table that accompanies Fig. 19.

Projection Welding of Powder Metallurgy Parts

In welding powder metallurgy parts (sintered compacts), it is essential to restrict the depth of melting (penetration) of the sintered metal at the joint interface to the shallowest depth that will produce consistent welds and adequate bond strength. In the following example, projection welding was used for attaching powder metallurgy parts to a low-carbon steel rim. The upper electrode was contoured to make contact with the entire upper surface of

the powder metallurgy part. An annular type of projection, provided by the sharp edge of the hole in the rim, was used to minimize nugget penetration in the sintered iron, and thus to produce a strong weld.

Example 402. Use of Conical Bosses To Minimize Penetration in a Powder Metallurgy Part in Welding It to Low-Carbon Steel (Fig. 20)

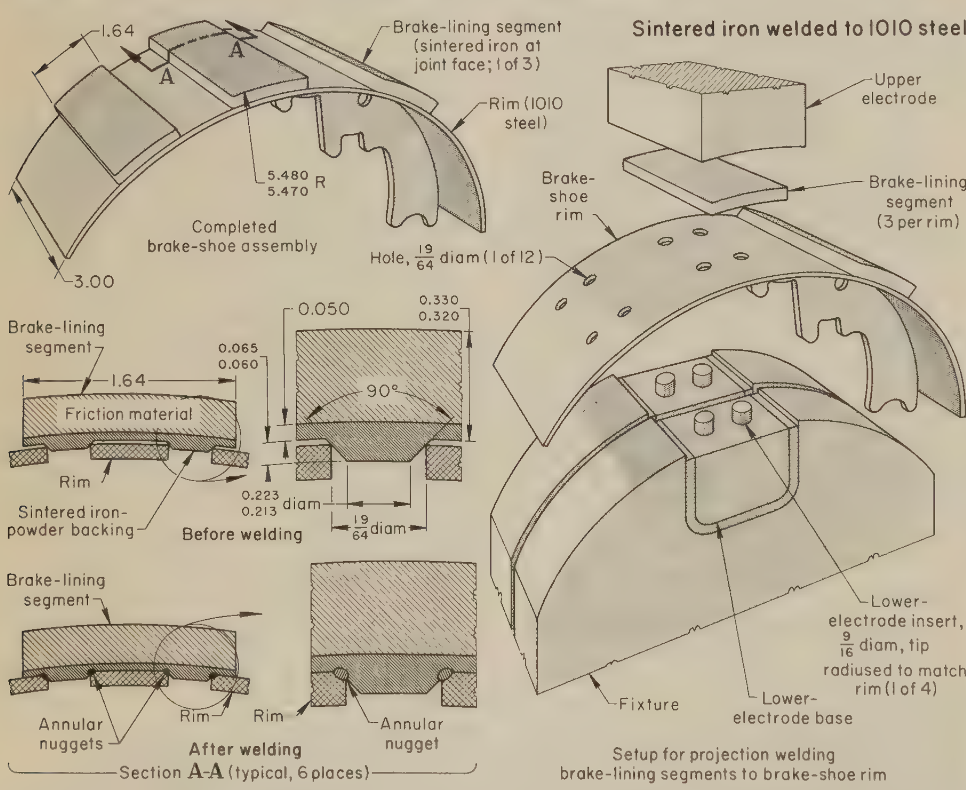
Three sintered powder metallurgy parts, consisting of a friction material and a backing that was made from low-density iron powder, were welded to a 1010 steel brake-shoe rim, as shown in Fig. 20, to serve as brake-lining segments. The friction material was developed for heavy-duty use in automotive drum-type brakes, and because of its composition, could not be expected to form acceptable projection welds with the brake-shoe rim. The sintered iron-powder backing layer of each brake-lining segment was joined to the rim by four projection welds.

Truncated-cone projections on the sintered backing (see section A-A in Fig. 20) were designed so that their conical surfaces would contact the sharp edges of the holes in the rim, to produce an annular nugget with shallow penetration into the sintered metal. This design avoided the formation of porous, weak welds that could have resulted from excessive melting of the sintered metal.

For welding, the rim was clamped in an indexed position on the fixture that held the lower electrodes (see view at right in Fig. 20). The first lining segment was positioned with the projections inserted in the holes in the rim, and the welding cycle was initiated by manually depressing two buttons. An air-operated ram lowered the upper electrode to make contact with the lining segment. This actuated the weld-sequence timer and the four welds were made. Then the ram and upper electrode were retracted, the assembly was indexed, and the operational sequence was repeated to weld the second and third lining segments to the rim. The finished brake shoe was manually removed from the fixture. Equipment details and welding conditions for this application are given in the table that accompanies Fig. 20.

The upper electrode, made of RWMA class 2 material, was radiused to fit the lining segment. The lower electrode consisted of a base made of class 2 material with four 9/16-in.-diam inserts made of class 11 material. The inserts were silver brazed to the base in positions that aligned with the holes in the rim. After about 12,000 assemblies had been welded, the lower electrode was removed from the machine and returned to the toolroom for dressing of the insert tips to the radius matching that of the rim.

Weld quality was spot checked with a destructive push-off test. In this test, the outside diameter of the rim was supported on both sides of a lining segment while force was applied hydraulically to the four projection welds to break them apart. The breaking load for the welds was the essential criterion of acceptance; weld shape and appearance were of minor significance in this application.



Equipment Details	
Welding machine	Manual press type, with 16-tap transformer
Rating at 50% duty cycle	175 kva
Electrodes	RWMA classes 2 and 11(a)
Electrode force, max	4500 lb
Heat control	Electronic tube type

Welding Conditions	
Welding current	35,000 amp
Heat-control setting	90%
Electrode force	1000 lb
Squeeze time	50 cycles
Weld time	22 cycles
Hold time	35 cycles

(a) Upper electrode was made of RWMA class 2 material and was radiused to fit the surface of the brake-lining segment; lower electrode consisted of four 9/16-in.-diam RWMA class 11 inserts radiused to conform to the inside surface of the rim and silver brazed to a class 2 base.

Fig. 20. Setup for joining three brake-lining segments, made of a friction material backed with sintered iron powder, to a steel brake-shoe rim with 12 projection welds, in which the use of truncated conical bosses on the lining segments minimized penetration into the sintered iron (Example 402)

Control of Weld Quality

High-quality joints can be produced consistently by projection welding if proper design of workpieces, correct welding conditions and a program of preventive electrode maintenance are used. Variations in dimensions and physical and mechanical properties of workpieces also affect weld quality.

Structures to be projection welded usually are designed so that the welds are in shear when the welded parts are stressed in tension or compression. Welds usually are inspected visually and by peel or tensile-shear tests.

The quality-control techniques for projection welding generally are the same as for resistance spot welding (page 417). For details of standard methods and quality-control procedures for projection welding, see AWS C1.1-66, Recommended Practices for Resistance Welding, Section V.

Penetration into the base metal can vary from 20 to 80% of the thickness of the thinner sheet. Full-penetration welds cause rapid deterioration of electrodes, are unsightly and may require excessive finishing, and are no stronger than normal-penetration welds. Insufficient penetration results from inadequate or unbalanced heating.

Porous welds usually are caused by overheating, inadequate welding or forging pressures, or too-late application of adequate forging pressure. Premature collapse of the projection and the presence of scale, oxide or other foreign material on the surface to be welded also can cause porous welds.

Effect of Work-Metal Properties. The composition, hardness or temper, dimensions, and mechanical properties of the work metal must be controlled within a suitably narrow range to consistently produce welds having uniform and acceptable size, penetration and strength.

In the example that follows, the tensile-strength specification range for incoming nickel wire had to be narrowed to obtain weld repeatability.

Example 403. Use of a Narrow Tensile-Strength Purchasing Specification To Ensure Repeatability of Cross-Wire Welds (Fig. 21)

Figure 21 shows a portion of a connector grid for an aerospace electronic assembly in which about 1800 cross-wire projection welds were made at right-angle intersections of 0.016-in.-diam nickel connector wires with each other and with component leads made of nickel alloys such as Kovar (53 Fe, 29 Ni, 17 Co) and Dumet (copper-clad 56 Fe, 42 Ni, 1 Mn). Four sizes of component leads, from 0.016 to 0.032 in. in diameter, were used, and both the wires and the leads were gold plated.

The matrix of nickel connector wires was constructed by making cross-wire welds at selected locations on the grid through openings in a polyester panel that separated transverse and longitudinal wires; nickel alloy component leads extending vertically through other openings in the polyester panel were later cross-wire welded to the nickel connector wires.

Original Method of Developing Welding Conditions. Originally, because of variations in the welding behavior of incoming connector-wire stock, each time a new lot of wire was received, welding conditions had to be revised for the 20 material combinations in which the wires were welded. The incoming wire was inspected for com-

pliance with material specifications, and new sets of machine settings were developed, with the aid of iso-strength diagrams, to meet stringent requirements in welding each of the 20 material combinations. This was done using a control machine to develop machine settings that could be applied to each of the 16 production machines used in the operation. Developing the welding conditions for each incoming lot of wire was time-consuming and costly. Also, production time was lost while qualification welds were made on all machines for each new lot of wire.

Qualification tests consisted of making 50 specimen cross-wire welds and testing them to destruction in torsion shear by pulling the legs into a straight line. The weld was required to hold until the legs were in a straight line, and to develop at least half the strength of the weaker of the two members. The strength of one of the 50 specimen welds was allowed to fall as low as 40% that of the weaker member of the joint. However, if more than one weld fell below 50%, or if one fell below 40%, new welding conditions had to be developed for the wire being sampled, and the testing program had to be repeated.

In addition to the strength requirement, the welds had to show setdown not greater than 35% total, and penetration into either wire not greater than 50%.

Process Study. In an attempt to reduce the cost and machine downtime involved in development and qualification of welding conditions, a study was made of the entire operation. It was found that variations in tensile strength of the nickel connector wire affected welding results more than any other single factor. (With electrode force and welding current held constant, the contact resistance of a work metal having lower tensile strength is lower than that of a metal having a higher tensile strength, because the lower-tensile-strength metal deforms more readily, increasing the contact area.) To obtain repeatability of sound welds, adjustments in welding conditions were found to be necessary whenever the tensile strength of the nickel wire varied by more than about ±2000 psi.

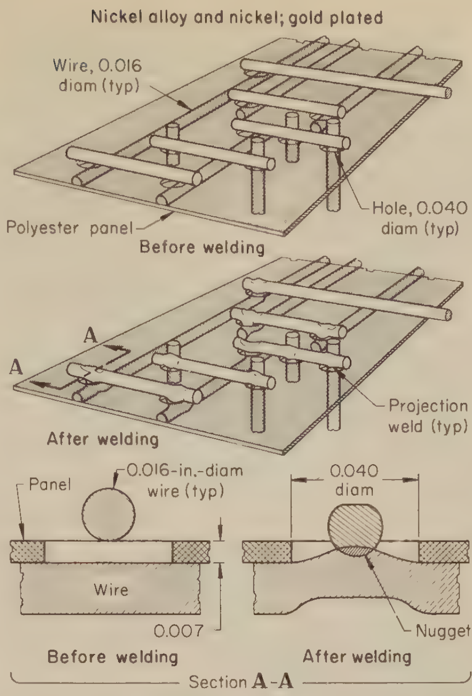
Routine control methods were found to be sufficient for holding all other material and operating factors within suitable limits. Uniformity of the component leads, which had less effect on welding behavior than uniformity of the connector wires, was ensured by narrow limits on chemical composition and diameter.

New Specification and Improved Method. The manufacturer narrowed the connector-wire tensile-strength range on the purchasing specification (formerly 60,000 to 85,000 psi) to 65,000 to 70,000 psi. By adhering to this range and by standardizing electrode force at 6 lb and electrode material as RWMA class 2, standard sets of welding conditions for the 20 material combinations were developed (on the control machine) that were suitable for use on every new lot of connector wire that passed incoming inspection. Thus, the number of welding schedules needed for the entire operation was reduced from 120 to 20.

The standardized welding conditions were programed into each machine, and setup required only that the operator push a button, according to worksheet instructions, to select the correct set of conditions.

Time Saving by Improved Method. Before the acceptable range of connector-wire tensile strength was narrowed, developing and qualifying sets of welding conditions for a shipment of incoming wire required a total of 412 hr — 320 hr for developing a new schedule for each of the 20 material combinations, 36 hr for making 50 sample welds for each material combination on each production machine, and 56 hr for inspecting and analyzing the results.

The improved procedure required a total of 9 hr — 1 hr for making tension tests on the incoming wire and 8 hr for making a total of 50 weld samples on the control machine using several material combinations and the established welding schedules, and testing the welds. Thus, a total of 403 hr was saved for each lot of connector wire by using the narrower acceptance range on tensile strength and the improved qualification method.



Conditions for Cross-Wire Welding

Welding machine	Capacitor-discharge type, bench mounted, equipped with low-inertia, fast-follow-up welding head
Electrode material	RWMA class 2
Electrode force	6 lb
Weld time	12 to 13 milliseconds
Production rates (approx):	
Matrix welds	2 per minute
Welds to component leads	1 per minute

Fig. 21. Portion of a connector grid, showing cross-wire welds for which a standardized welding program was developed on the basis of tensile strength of as-purchased connector wire (Example 403)

Nondestructive techniques for pretesting weldability of workpieces may be of special value in applications requiring extremely high weld reliability, such as those in which the workpieces are costly, in which many critical welds must be made on a complex assembly, or in which weld repair is difficult, costly or impossible. One nondestructive method for the testing of weldability that sometimes, if necessary, can be applied to 100% of the work metal (instead of only to samples, as when destructive tests are used), is measurement of a magnetic or electrical property of the workpiece that is related to weldability. Inductance, for instance, can be measured accurately and rapidly on parts of suitable shape and controlled dimensions, and can be used as an index of weldability in relation to known standards, as in the following example.

Example 404. Use of an Inductance Test in Place of a Destructive Pull Test, To Reduce the Time Needed for Determining Weldability of Wire Leads

Wire leads on components used in a space-module electronic assembly were joined to connector wires by cross-wire projection welding. Conformance to material specifications for all leads and connector wires was checked and wire diameter was measured before welding.

Originally, to test weldability before making a production run, the leads on 5% of the components in a production lot were welded to connector wires, and the welds were pull tested to determine weld quality. The test welds were made at the ends of the leads so that the components could still be used in assemblies, but occasionally components were rendered unusable by the testing procedure. (A description of the materials, welding operation and pull test is given in Example 403.)

In an improved testing method, the inductance of the lead wire, found to be directly correlated to its weldability, was measured on a commercially available instrument. Master lead wires were made of each material that was to be tested and these were used to establish standard meter readings. The inductance of the specimen lead had to match, or approach, that of the master lead within ±1.5 units of scale reading.

At first, the inductance of all component leads was measured before release to production, and those components with leads that failed to pass the inductance test were salvaged by welding under conditions based on tension tests and trial-and-error development. Later, it was found satisfactory to measure the inductance of the leads on a 5% sampling basis. As a continuing check on the validity of the inductance measurement as an index to welding behavior of the leads, sample leads were welded at regular intervals and pull tested to check the strength of the weld.

Metals used for master wires were selected samples of the materials used in cross-wire welding, and included: nickel (99 Ni), Kovar (53 Fe, 29 Ni, 17 Co), and Dumet (copper-clad 56 Fe, 42 Ni, 1 Mn); lead-wire diameters ranged from 0.016 to 0.032 in., and all leads (and connector wires) were gold plated.

In the original method, welding and pull testing required 7 minutes per sample. In the improved method, measuring the inductance of leads on 5% of the components and inspecting 1% of the welds by pull testing took an average of 1.5 minutes per sample, and thus, average testing time was reduced by 5.5 minutes per sample.

Projection Welding vs Other Joining Processes

In some applications, projection welding can be used as an alternative to other welding processes and to some mechanical processes for joining workpieces. In Example 396, unit cost was reduced substantially when projection welding replaced riveting in production of a platen-frame assembly. The next three examples describe applications in which projection welding replaced spot welding, shielded metal-arc welding, and staking.

Projection Welding vs Spot Welding. For some applications, greater productivity can be obtained by using projection welding rather than spot welding, because closely spaced spot welds must be made one at a time whereas two or more closely spaced projection welds can be made simultaneously. Two applications in which projection welding provided increased production rate and lower cost, in comparison with spot welding, are described in Examples 388 and 389 (see page 436).

In the example that follows, when spot welding was replaced by projection welding, production rate was increased, and weld consistency and the appearance of workpiece surfaces (elimination of indentations) were improved.

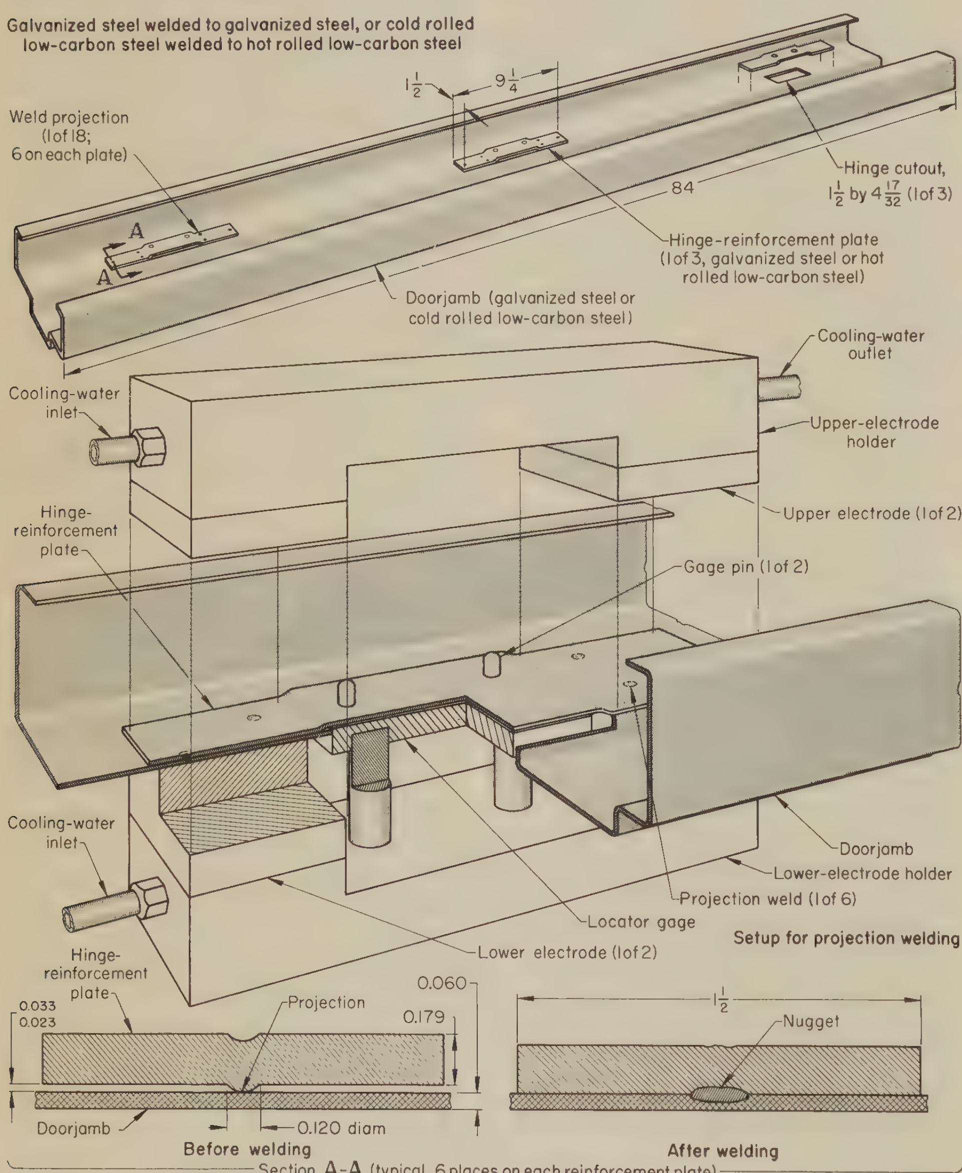
Example 405. Change From Spot Welding to Projection Welding That Improved Weld Quality and Appearance and Increased Production (Fig. 22)

Three hinge-reinforcement plates were joined to a steel doorjamb by means of six projection welds in each plate, as shown in Fig. 22. Originally, the 18 welds were made one at a time by spot welding in a 50-kva rocker-arm machine. To increase production and to improve the appearance of the finished product by eliminating electrode marks, the process was changed to projection welding.

For the improved method, the spot welding machine was replaced with a 150-kva press-type resistance welding machine, and the electrodes shown in Fig. 22 were built. Also, the punch-press tooling was rebuilt to include an operation in which projections were formed in the reinforcement plate. For welding each hinge-reinforcement plate, the doorjamb was positioned with a hinge cutout over the locator gage, and a plate was placed on the two gage pins (see Fig. 22). The upper electrodes were lowered and the six projection welds were made simultaneously, in about the same time that had been required to make one spot weld. In addition, repositioning of the doorjamb for each of the spot welds was eliminated. Thus, with projection welding, output was increased about sixfold.

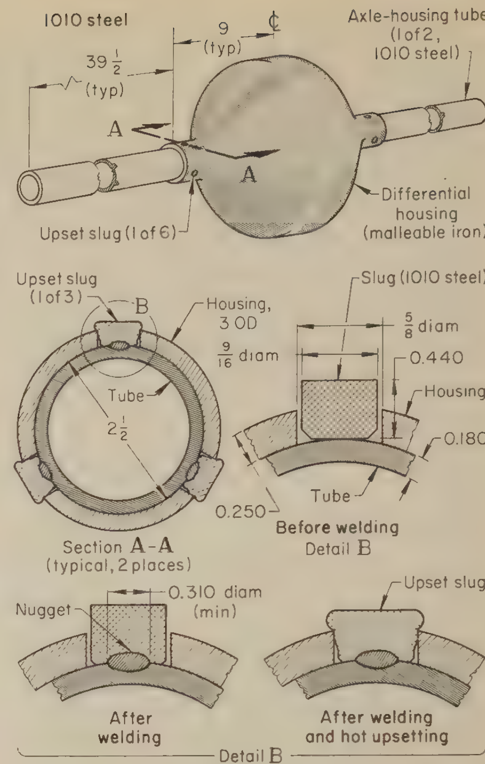
Because of the large area of the upper and lower electrode faces, there was no indentation at the welds, and thus, one of the major drawbacks of the original spot welding procedure was eliminated.

The welded assemblies were examined visually to ensure proper placement of the reinforcement plates and to establish that the projections had been flattened. The plates were struck with a special mallet to test weld soundness. Inspectors subjected one out of every 1200 welded doorjambs to destructive peel and pull tests; the requirement for acceptance was that, for each weld, a nugget be pulled out of the doorjamb, which was the thinner workpiece.



Welding machine	Press-type combination spot and projection
Rating at 50% duty cycle	150 kva
Electrode material	RWMA class 3
Electrode holders	Cold rolled copper
Welding current	70,000 amp
Electrode force	2100 lb
Squeeze time	20 to 40 cycles
Weld time	22 cycles
Hold time	3 cycles
Production rate	250 assemblies per hour

Fig. 22. Assembly of a doorjamb and three hinge-reinforcement plates, for which change from spot welding to projection welding under the conditions listed in the table improved weld quality and appearance and increased production (Example 405)



Equipment Details

Welding machine	Three-station projection welding machine with two eight-tap transformers per station and heat control for welding and upsetting
Rating at 50% duty cycle	100 kva(a)
Electrodes	RWMA class 2, ⅝-in. diam, type C (flat) face(b)
Current, max	35,000-amp ac(a)

Conditions for Welding and Upsetting

Current	Welding, 22,000 amp; upsetting, 15,000 amp
Electrode force	Welding, 2000 lb; upsetting, 3000 lb
Weld time	20 cycles
Cool time	20 cycles
Upset time	30 cycles
Production rate:	
Subassemblies per hour	150
Welds per hour	900

(a) For each transformer. (b) Electrodes hydraulically driven.

Fig. 23. Drive-train housing subassembly joined with three hot upset projection welded slugs, which replaced shielded metal-arc plug welds (Example 406)

Depending on customer requirements, one of two work-metal combinations was used — galvanized steel doorjamb and reinforcement plate, or cold rolled low-carbon steel doorjamb and hot rolled low-carbon steel plate. When uncoated steel was welded, the projection welding electrodes were dressed by milling after four hours. In welding galvanized steel components, zinc rapidly built up on the electrodes, and the electrodes were dressed about every two hours.

The effectiveness of the electrode design and operating procedure adopted for projection welding was demonstrated convincingly by the reduced frequency of electrode dressing, as compared to that necessary when welding by the original spot welding method. The spot welding electrodes had been dressed by hand once an hour in welding bare steel parts, and after every two or three doorjambs in welding galvanized steel parts.

Equipment details and conditions for projection welding are given in the table that accompanies Fig. 22.

Projection Welding vs Arc Welding. Nonweldable components are sometimes joined to weldable components

by means of a mechanical fastener that has been arc welded to the weldable component. Where the assembly sequence or the part design and dimensions prevent access for welding in this manner, arc plug welds can be deposited through holes in the nonweldable member.

Projection welding also can be used for attaching fasteners in joining nonweldable and weldable components; it is fast, and can be done where there is no access for arc welding. Also, projection welding allows the use of a low, controlled heat input to avoid damage to adjacent heat-sensitive components, as shown in the example that follows.

Example 406. Change From Shielded Metal-Arc Plug Welds to Upset Projection Welded Slugs for Joining Steel and Malleable Iron (Fig. 23)

A housing subassembly for a drive train (see Fig. 23) consisted of a malleable iron differential housing and two 1010 steel axle-housing tubes, which were press fitted into the neck of the housing.

Originally, the subassembly was joined by means of shielded metal-arc plug welds, deposited in equally spaced holes drilled through the neck of the cast housing; fusion of the deposits was mainly with the steel tubes. The weld-metal plugs acted as drive pins to transmit torque or thrust from one component to the other. This method of joining, however, was unsatisfactory for several reasons: heat from welding often cracked the malleable iron, fusion to the axle-housing tubes was erratic, welds were porous because of an oil-like sealing compound entrapped between the housing and the tubes, and the confined working area made accessibility for arc welding difficult. Other arc welding methods, including automatic gas metal-arc welding, were considered for the plug welding, but were rejected because all were slow and involved a high heat input.

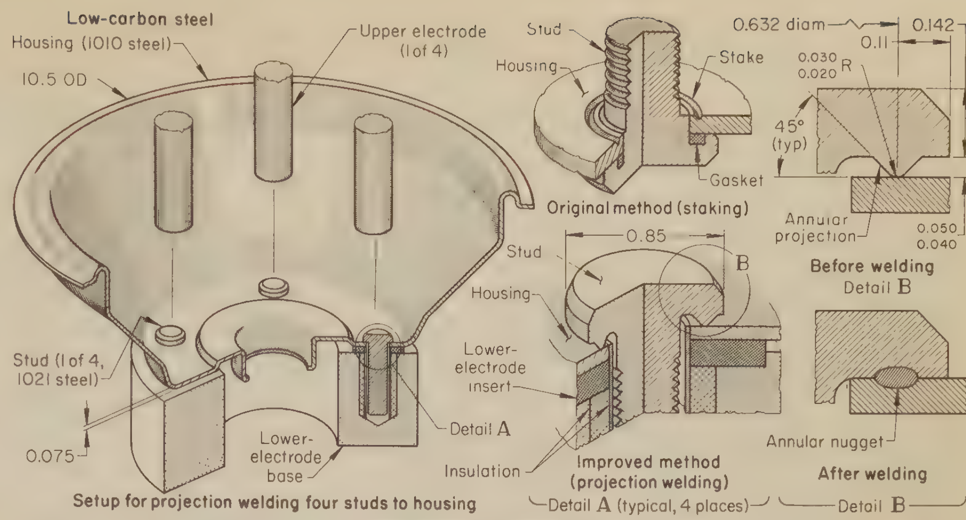
In an improved method of joining the three components (see Fig. 23), in which a three-station projection welding machine was used, three slugs of 1010 steel were inserted in the holes in each end of the cast housing, and were projection welded to the steel axle-housing tubes. The curvature of the tube functioned as a projection for welding.

Two welds were made at once, one on each end of the cast housing. The welds were series welds; a return electrode was clamped to each tube. The subassembly was rotated 120° and transferred to the next station to make the second pair of welds, and these operations were repeated to make the third pair of welds. After each projection weld was completed, the slug was heated by a second impulse and was hot upset by the electrode. The upset slugs partly filled the holes in the housing, and thus served as mechanical retaining pins.

The much lower heat input to the welds, as compared to that for shielded metal-arc plug welding, greatly reduced the volatilization of sealing compound, and resulted in an acceptably low level of weld porosity.

Subassemblies joined by the improved method were able to withstand 38,000 lb-in. of torque. One subassembly per shift was torque tested to destruction. Production rate was 150 subassemblies per hour. Equipment details and conditions for projection welding and upsetting are given in the table with Fig. 23.

Projection Welding vs Staking. Studs in housings are commonly staked and are thus held with adequate rigidity until the assembly is completed and a nut on the end of each stud holds it secure. But in housings for which exceptionally high integrity is needed (as, for instance, in a housing required to be leakproof under air pressure), projection welding can sometimes produce a superior joint, as in the following example.



Equipment Details	
Welding machine	Special four-post, semiautomatic, with two eight-tap transformers
Rating at 50% duty cycle	150 kva each
Upper electrodes	RWMA class 2
Lower electrodes	RWMA class 11 inserts, silver brazed to a class 2 body
Electrode force, max	6650 lb per electrode
Controls	Individual solid-state control devices for each stud

Welding Conditions	
Welding current	50,000 amp
Heat-control setting	80% and No. 7 tap
Electrode force	4700 lb per electrode
Squeeze time	55 cycles
Weld time	6 cycles
Hold time	10 cycles
Production rate:	
Assemblies per hour	180
Welds per hour	720

Fig. 24. Brake-booster housing for which changing from staking to projection welding of studs improved joint tightness (Example 407)

Example 407. Change From Staking to Projection Welding of Studs That Improved Joint Tightness (Fig. 24)

In the brake-booster housing shown in Fig. 24, the joints between the four studs and the housing were required to be leakproof under air pressure of 25 psi. Also, each stud had to be perpendicular to the mounting surface of the housing, within 0.005 in. at the tip of the protruding end of the stud, and to withstand 30 lb-ft torque.

Originally, the four studs were assembled to gaskets and were joined to the housing by staking (see "Original method" view in detail A in Fig. 24). With staking, however, rejection rate was 15%, because of joints that failed to withstand leak tests.

The rejection rate was reduced to 0.6% by changing the method of joining to projection welding, using an annular projection formed on the lower surface of the head of the stud, as shown in details A and B in Fig. 24. The projection welds were made in a four-electrode fixture that was designed to receive the housing in the open-side-up position (see view at left in Fig. 24), and that consisted of four lower-electrode inserts, each with a hole in the center to accept the threaded end of the stud. The inserts were mounted on a common base that made it possible to remove, dress and replace them as a unit.

The welding machine had two transformers for supplying the welding current and four air cylinders for supplying the electrode force. One upper electrode was mounted on each air cylinder, and the welds were made one at a time, using a separate transformer for each weld.

For welding, the housing was placed open side up on the lower electrodes, and studs were inserted into holes in the housing. The welding cycle was started by depressing double palm buttons. The two front upper electrodes were brought in contact with the studs; the left stud was welded using the left transformer, and after a few cycles delay, the right stud was welded with the right transformer. Then the two front electrodes were retracted, the two rear electrodes were brought in contact with the other two studs, and welding was done in the same sequence. After the two rear electrodes were retracted, the assembly was automatically ejected onto a conveyor.

The parts were spot checked for leakage, which was seldom found, and for strength. In the strength test, the stud was pushed from the housing, and the weld was required to be strong enough to tear a slug from the housing metal. In a final series of checks, all completed housings were tested for leaks.

In addition to reducing the rejection rate, the change from staking to projection welding eliminated the cost of the gasket and of assembling the gasket to the stud. Production rates for the two methods were about the same.

The electrodes were removed after each shift, or after welding about 1440 assemblies, and were sent to the toolroom for machine dressing. After being re-dressed five times, the upper electrodes and the lower-electrode inserts were replaced. Equipment details and welding conditions are given in the table with Fig. 24.

Table 8. Examples of Projection Welding Presented Elsewhere in This Volume

Example	Subject of example
408	Type 430 stainless steel welded to type 440A; eight projections were welded at a time
416	Joining type 302 stainless steel cover plate and bracket for close alignment, blemish-free appearance and high production rate
417	Cross-wire welding food-handling trays of type 304 stainless steel; low setdown avoided discoloration
425	Capacitor-discharge welding gold-plated nickel wire to solder-clad beryllium copper strip
426	Beryllium copper sandwiched between low-carbon steel that was welded to low-carbon steel
427	Annular projection coined into a cartridge brass lead wire during flattening, then welded to a red brass terminal
428	Closely spaced projections joined switch elements made of phosphor bronze and cartridge brass

Resistance Welding of Stainless Steel

*By the ASM Committee on Welding and Brazing of Stainless Steel**

STAINLESS STEELS are readily resistance welded by spot, seam and projection methods. Generally the weld time and welding current are less than those used for welding carbon steel, but electrode force is usually greater.

Austenitic stainless steels of the 300 series are resistance welded more often than any other metal except carbon steel of low carbon content. Preferably, stainless steel to be resistance welded should contain a maximum of 0.08% carbon (as in types 304, 316 and 347), although steels with a higher carbon content, such as types 301, 302, 309 and 310, frequently are resistance welded with good results.

The martensitic and ferritic types of stainless steel both can be welded satisfactorily. The martensitic types are less frequently resistance welded, because joints made in them are hard and brittle in the as-welded condition. Exact control of welding conditions is required, and for best results a postweld tempering treatment should be used. Table 1 gives nominal compositions and pertinent physical properties of the types of stainless steel that are commonly resistance welded.

Weld Strength. The minimum breaking load of spot welds in shear is given in Tables 2 and 3. Resistance welds in austenitic and precipitation-hardening stainless steels, if postweld heat treated, provide good service at cryogenic temperatures.

Spot, projection and seam welds in austenitic stainless steel have high corrosion resistance in most atmospheric environments, because appreciable formation of intergranular carbide is not likely to occur in resistance welds during the short weld times used for most resistance welding applications. Resistance of the solution-treated base metal to intergranular corrosion is less likely to be affected adversely than when conventional arc welding, with its longer weld times, is used. (See the sections on Welding Characteristics of Austenitic Stainless Steel, this page, and Welding Characteristics of Martensitic and Ferritic Stainless Steels, next page.)

Equipment. Less transformer capacity is required for resistance welding of stainless steel than for welding equivalent thicknesses of any other metal, with all other welding conditions being the same.

The machines use a single-phase alternating-current power supply, or a three-phase rectifier or frequency-converter power supply. A weld made with a three-phase power supply usually requires slightly higher current and a longer weld time than a weld made with a single-phase supply. The force, material and shape of the electrodes are similar for both single-phase and three-phase power supplies.

Synchronous timing controls are preferred for resistance welding stainless steel, because a variation of one or two cycles in the short weld time can result in a large percentage change in weld time. Current and voltage regulators may be desirable, depending on machine size and power-supply capacity.

Factors Affecting Resistance Welding of Stainless Steel

The characteristics of austenitic stainless steel that necessitate careful attention to the details of operation include sensitivity to heat, low electrical conductivity, low thermal conductivity, high melting temperature, high strength at elevated temperature, high coefficient of thermal expansion, and high contact resistance.

Sensitivity to Heat. The corrosion resistance of stainless steels, which generally is the principal reason for their use, may be adversely affected by heat. In resistance welding, the temperature generated and the time at temperature must be controlled accurately to hold the adverse effects of heat (principally carbide precipitation) to a minimum, while at the same time applying enough heat and pressure to obtain the desired weld properties.

Electrical Conductivity. The low electrical conductivity of stainless steels, compared with that of plain carbon steel, results in faster generation of heat with the same current. Therefore, in welding stainless steel, compared with welding similar thicknesses of carbon steel, a lower welding current or a shorter weld time, or both, should be used. Relative values of electrical conductivity of stainless steels that are commonly resistance welded are given in Table 1. These values are in relation to copper alloy 102 (oxygen-free copper), which is rated at 101% by the International Annealed Copper Standard (IACS) and has an electrical resistivity of 1.72 microhm-cm. Low-carbon steel has a relative electrical conductivity rating of 13.7% IACS, or an electrical resistivity of 12.5 microhm-cm.

Thermal Conductivity. Stainless steel has thermal conductivity lower than that of carbon steel. Therefore, heat is conducted away from the weld zone more slowly than in carbon steel. Relative values of thermal conductivity of stainless steels that are commonly resistance welded are given in Table 1.

Melting temperatures of stainless steels also have an effect on the amount of heat required to produce fusion for welding. The austenitic stainless steels melt in various ranges between 2500 and 2650 F, and the martensitic and ferritic alloys melt in ranges between 2550 and 2790 F. Plain low-carbon steel melts at temperatures between 2700 and 2800 F.

High strength at room and elevated temperatures of the austenitic stainless steels and, to a lesser extent, of the straight-chromium grades, makes it necessary to use greater electrode force to bring the work-metal surfaces together in the required intimate contact at points of welding than is required for carbon steel.

Thermal Expansion. The austenitic stainless steels expand and contract with changing temperature to a greater extent than does plain carbon steel. These dimensional changes and the slower heat diffusion in austenitic stainless steel result in greater thermal stress, which leads to warping. The coefficient of thermal expansion of austenitic stainless steel between 32 F and 1800 F ranges from 10.6 to 11.4 micro-in. per inch per °F, compared with 8.1 micro-in. per inch per °F for plain low-carbon steel.

The straight-chromium grades of stainless steel (martensitic and ferritic) have coefficients of thermal expansion lower than that of plain carbon steel. The corresponding coefficients over the range of 32 to 1800 F are 6.4 to 7.6 micro-in. per inch per °F for these stainless steels.

The effect of thermal expansion on assemblies that are joined by spot and projection welding usually is minimal because of the relatively small area that is heated during welding. In seam welding, however, the effect is greater, because welding is continuous. (See "Effect of Heat Distortion", page 461 in the section on Resistance Spot Welding, and "Heat Distortion", page 461 in the section on Resistance Seam Welding and Roll Resistance Spot Welding.)

Contact resistance of stainless steels is higher than that of carbon steel, and therefore greater electrode pressure is needed to make good resistance welds. Preweld cleaning is necessary for maintaining uniform contact resistance. (See "Surface Preparation for Welding", on the next page.)

Welding Characteristics of Austenitic Stainless Steel

Austenitic stainless steel, in the solution-annealed condition, contains carbon in solid solution. When the steel is heated to the temperature range of 800 to 1500 F, carbon combines with chromium, resulting in chromium carbide precipitation at the grain boundaries. Carbide precipitation makes the material more sensitive to intergranular corrosion. Sensitization to intergranular corrosion is governed in austenitic stainless steel by (*a*) the carbon content; (*b*) the solubility of the carbon; (*c*) the presence of one or more stabilizing elements; (*d*) the proximity of the actual metal temperature to 1200 F

*For committee list, see page 245. Some of the examples in this article were contributed by members of other Metals Handbook welding committees.

within the 800 to 1500 F range; and (*e*) the time period during which the metal is held in that temperature range. The first three factors are controllable only through selection of composition; the latter two are controllable by adjustment of welding conditions such as heat input, size of spot, production rate, and provisions for cooling.

Table 1. Nominal Compositions and Physical Properties of Austenitic, Martensitic, Ferritic and Precipitation-Hardening Stainless Steels That Are Commonly Resistance Welded

Type	Nominal composition, % C, max	Mn, max	P, max	S, max	Si, max	Cr	Ni	Other	Relative thermal conductivity, %(a)	Relative electrical conductivity, % IACS (b)	Melting range, F
Austenitic Stainless Steels											
301	0.15	2.0	0.045	0.03	1.0	17.0	7.0	...	4.2	2.4	2550-2590
302	0.15	2.0	0.045	0.03	1.0	18.0	9.0	...	4.2	2.4	2550-2590
304	0.08	2.0	0.045	0.03	1.0	19.0	9.3	...	4.2	2.4	2550-2650
304L	0.03	2.0	0.045	0.03	1.0	19.0	10.0	...	4.2	2.4	2550-2650
309	0.20	2.0	0.045	0.03	1.0	23.0	13.5	...	4.0	2.2	2550-2650
310	0.25	2.0	0.045	0.03	1.5	25.0	20.5	...	3.6	2.2	2550-2650
314	0.25	2.0	0.045	0.03	2.0	24.5	20.5	...	4.5	2.2	...
316	0.08	2.0	0.045	0.03	1.0	17.0	12.0	2 to 3 Mo	4.2	2.3	2500-2550
316L	0.03	2.0	0.045	0.03	1.0	17.0	12.0	2 to 3 Mo	4.2	2.3	2500-2550
317	0.08	2.0	0.045	0.03	1.0	19.0	13.0	3 to 4 Mo	4.2	2.3	2500-2550
321	0.08	2.0	0.045	0.03	1.0	18.0	10.5	Ti (min), 5×C	4.1	2.4	2550-2600
347	0.08	2.0	0.045	0.03	1.0	18.0	10.5	(c)	4.1	2.4	2550-2600
348	0.08	2.0	0.045	0.03	1.0	18.0	11.0	(d)	4.1	2.4	2550-2600
Martensitic Stainless Steels											
403	0.15	1.0	0.04	0.03	0.5	12.3	...	...	6.4	3.0	2700-2790
410	0.15	1.0	0.04	0.03	1.0	12.5	...	...	6.4	3.0	2700-2790
414	0.15	1.0	0.04	0.03	1.0	12.5	2.0	...	6.4	2.5	...
431	0.20	1.0	0.04	0.03	1.0	16.0	2.0	...	5.2	2.4	2550-2650
440A	(e)	1.0	0.04	0.03	1.0	17.0	...	0.75 max Mo	6.2	2.9	2500-2750
Ferritic Stainless Steels											
405	0.08	1.0	0.04	0.03	1.0	13.0	...	0.1 to 0.3 Al	6.9	2.9	2700-2790
430	0.12	1.0	0.04	0.03	1.0	17.0	...	...	6.7	2.9	2600-2750
430F	0.12	1.25	0.06	(f)	1.0	17.0	...	0.6 Mo (opt)	6.7	2.9	2600-2750
442	0.20	1.0	0.04	0.03	1.0	20.5	...	...	5.5	2.7	2600-2750
446	0.20	1.5	0.04	0.03	1.0	25.0	...	0.25 max N_2	5.3	2.6	2600-2750
Precipitation-Hardening Stainless Steels											
17-7 PH	0.07	0.70	0.02	0.01	0.4	17.0	7.0	1.15 Al	4.3	2.1	2590-2640
PH 15-7 Mo	0.07	0.70	0.02	0.01	0.4	15.0	7.0	2.25 Mo, 1.15 Al	4.2	2.1	2590-2640

(a) Based on copper alloy 102, which has a thermal conductivity of 226 Btu/hr/sq ft/ft/°F at 68 F, as 100%. Low-carbon steel has a thermal conductivity of about 13% on this relative scale. (b) International Annealed Copper Standard, volume basis at 68 F. For comparison, copper alloy 102 (oxygen-free copper) is 101% and low-carbon steel (1010) is about 14%. (c) Minimum columbium-plus-tantalum content, 10×C. (d) Minimum columbium-plus-tantalum content, 10×C; Co, 0.20 max; Ta, 0.10 max. (e) Carbon range, 0.60 to 0.75. (f) Minimum sulfur, 0.15.

Variations in composition among the standard austenitic stainless steels affect both the behavior of the steels in welding and their performance in service. Types 302, 304 and 304L differ chiefly in carbon content, which determines the amount of chromium carbide precipitation that can occur in the heat-affected zones of the base metal. In extra-low-carbon austenitic steels, the carbon content of which does not exceed 0.03%, carbide precipitation and susceptibility to intergranular corrosion are negligible. Types 316, 316L and 317 contain additions of molybdenum for improved corrosion resistance. In welding, the presence of molybdenum is both beneficial and harmful. Stabilized stainless steels, including types 321, 347 and 348, contain additions of titanium or of columbium-plus-tantalum that form preferential carbides that do not decrease resistance to intergranular corrosion, and thus effectively prevent intergranular chromium carbide precipitation during welding.

The effect of welding heat in producing carbide precipitation is discussed more fully in the article on Arc Welding of Stainless Steel, page 245.

The free-machining grades of austenitic stainless steel contain elements such as sulfur, phosphorus and lead that are intentionally added to improve machinability. These steels are not recommended for resistance welding. However, acceptable welds are frequently made in these grades by using shorter weld times than those normally used for welding stainless steel, and fast follow-up of electrode force.

Welding Characteristics of Martensitic and Ferritic Stainless Steels

The martensitic steels most often welded are types 403, 410, 414 and 431. These steels can be resistance welded in the annealed, hardened or hardened-and-tempered condition. Regardless of prior condition, welding produces a hardened martensitic zone adjacent to the weld. The hardness of this zone, although it can be controlled to a degree by the welding procedure, depends mainly on carbon content. As the hardness of the metal in the heat-affected zone increases, its susceptibility to cracking increases and its toughness decreases. Steels having a maximum carbon content of 0.15%, such as types 403 and 410, often produce satisfactory welds without postweld heat treatment. Steels with higher carbon contents, such as types 420 and 440A, generally require postweld heat treatment.

Chromium content also significantly affects welding behavior.

The ferritic grades of stainless steel most commonly welded are types 405, 430, 442 and 446. Resistance welds in these steels are brittle at room temperature, and if their use in the as-welded condition is unsuitable, annealing must follow welding. Postweld annealing, in addition to reducing brittleness, helps to restore normal resistance to corrosion. In most corrosive environments, ferritic stainless steels are less corrosion resistant than are austenitic stainless steels.

Surface Preparation for Welding

Oil or grease must be removed from the surfaces to be welded. Otherwise, carbon from the oil or grease can be absorbed into the steel, thus increasing the susceptibility of the steel to intergranular corrosion.

Protective adhesive paper used to prevent damage to the surfaces of polished sheets can become oil-soaked during press operations and cause the adhesive to stick to the sheet. This adhesive must be removed before resistance welding.

Burrs should be removed from the overlapping edges of components being resistance welded. Failure to remove burrs can cause the current to shunt through the burr instead of passing through the point of electrode contact.

Stainless steel sheets should not be ground or filed with tools used for ordinary steel, because even very slight iron contamination can reduce the effective chromium content in the ground or filed region and cause rejection of the weldment. Wire brushing must be done only with brushes made of stainless steel.

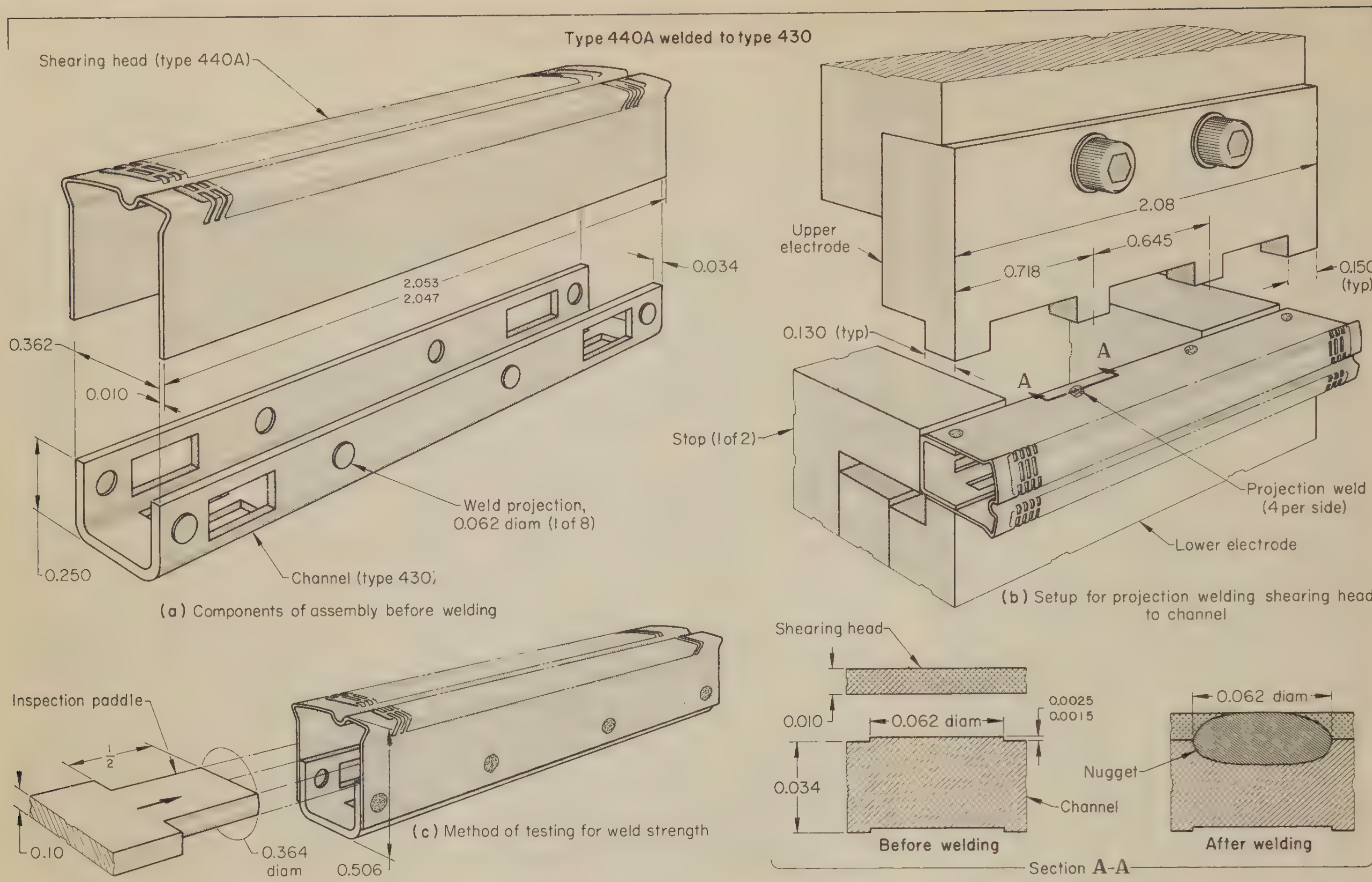
The chromium oxide that is formed on hot rolled stainless steel must be removed by pickling before the metal is resistance welded. The protective film that forms at ordinary temperatures after pickling is of microscopic thickness and usually does not interfere with resistance welding.

Special etching or chemical cleaning sometimes is needed, as in the following example.

Example 408. Elimination of Oxide Coating To Ensure a Strong Bond in Projection Welding (Fig. 1)

Projection welds joining the shearing head of an electric shaver to its mating channel (Fig. 1a) failed if the surfaces of the components were not adequately cleaned prior to welding. The channel (type 430 stainless steel) was cleaned and deburred by tumbling in a steel barrel containing a special soap solution and was then rinsed in water. The surface of the shearing head (type 440A stainless steel), however, needed special cleaning, because in a previous heat treatment it had developed a light oxide film that increased the contact resistance and acted as a barrier to heat penetration.

To minimize discoloration of the shearing head during heat treating (to Rockwell C 57), the heat treatment was conducted in a vacuum furnace in an atmosphere of prepurified nitrogen with a dew point of −60 F. Nevertheless, a light film of oxide occasionally formed on the surface and had to be removed by pickling the head in 25 to 50% hydrochloric acid at room temperature for a maximum of 30 sec. After pickling, the head was rinsed thoroughly and subjected to a passivating treatment that consisted of immersing the head for 15 min in an aqueous solution of nitric acid maintained at 18° to 21° Be and containing 2½ oz of sodium dichromate per gallon of so-



Equipment Details and Welding Conditions for Projection Welding

Power supply	440 v, single phase, 60 cycle	Electrodes	RWMA class 3(a)	Electrode force	165 lb
Welding machine	Press type, semiautomatic	Electrode force, max	660 lb(b)	Squeeze time	90 cycles
Transformer rating at 50% duty cycle	30 kva	Welding controls	(c)	Weld time	1 cycle
Secondary current, max	4.23 v, 31,000 amp	Welding current	12,000 amp, ac	Hold time	1 cycle
Transformer taps	Eight	Heat-control setting	No. 7 tap and 90%	Production per hour	750 assemblies(d)

(a) ⅝ by 2.08 in., with four faces 0.150 by 0.130 in. (b) At 80-psi air pressure. (c) Synchronous, with phase-shift heat control. (d) 6000 welds.

Fig. 1. Stainless steel shearing head and channel for an electric shaver, setup in which the assembly was projection welded, and method of testing for weld strength by insertion of an inspection paddle (Example 408)

lution. The solution temperature was maintained at 120 to 140 F. To avoid stress corrosion, the chloride content of the bath could not exceed 120 parts per million.

The head-and-channel assembly was positioned between upper and lower electrodes to make eight projection welds at one time (four to a side), as shown in Fig. 1(b). An inner supporting mandrel was not needed during welding, because the stiffness of the channel was sufficient to support the 165-lb electrode force. Adequate heat penetration at the joint surface was obtained by using electrodes made of RWMA class 3 material. Additional welding conditions are given in the table with Fig. 1. After being welded, the assembly was rinsed in flowing water, immersed for 10 min in an alkaline cleaner, and then rinsed again in flowing water.

The welded assemblies were tested for weld strength with a 0.364-in.-diam inspection paddle, as shown in Fig. 1(c). This tool was inserted between the walls of the head above the channel and rotated clockwise and counterclockwise until it touched the edge of the channel. The tool was then moved sideways with light pressure. Two out of every 50 assemblies were tested by the operator. If all the welds on both test assemblies held, welding was continued. If one weld failed, another assembly was tested. If this assembly passed, production was continued; if it failed, production was stopped until the difficulty was corrected. If there were two failures in any test interval, production was stopped. Periodic checks were also made by inspectors to ensure an acceptance quality level not exceeding 2.5% in defective assemblies. Dimensions were checked for two out of every 100 assemblies.

During setup, welds were sectioned and etched to determine nugget size, and hardness readings were taken. Microhardness readings across the weld area in the type 440A steel were 370 Knoop at the center of the weld metal, 672 Knoop at the edge of the weld, and 703 Knoop a short distance into the heat-affected zone. At a distance of about 0.0015 in. from the weld interface, the hardness of the 430 stainless steel was 423 Knoop, and at 0.008 in. it was 253 Knoop. The base-metal hardness was 240 Knoop (Rockwell 30-T 74).

Resistance Spot Welding

Resistance spot welding of stainless steel does not differ greatly from resistance spot welding of carbon steel, but the composition and physical properties of stainless steel make it necessary to control weld time and welding current more closely.

Table 2 gives recommended practices for resistance spot welding of series 300 austenitic stainless steels. The values in Table 2 are intended for use as starting points and should be adjusted to suit conditions and job requirements. The procedure for establishing a spot welding schedule on page 417 in the article on Resistance Spot Welding can be followed in making the adjustments.

Welding Current. The electrical conductivity of stainless steel is 15 to 25% that of carbon steel of similar carbon content, and the melting temperature, about 90%. Therefore, the heat for welding, and thus the welding current, should be less than for carbon steel. The values of welding current suggested in Table 2 for welding stainless steel vary from half as much as, to the same as or slightly more than, those suggested for welding carbon steel in Table 4 on page 414 in the article on Resistance Spot Welding in this volume. The welding currents are not in strict proportion to the electrical conductivities and melting temperatures, because other variables require that adjustments be made in weld time and electrode force.

Weld Time. The relative thermal conductivities of austenitic and precipitation-hardening stainless steels are 30 to 35% that of carbon steel. Because the heat is not conducted away from the weld area as rapidly as in carbon steel, less weld time is needed. Also, the weld time usually is so short that it must be precisely controlled because a variation of ±1 cycle may be exces-

sive. In stainless steel 0.062 in. thick, a variation of ±1 cycle would be ±10% of the weld time (Table 2), but for a thickness of 0.006 in., a variation of ±1 cycle would correspond to a variation of ±50% of the weld time.

Electrode Force. The contact resistance and strength of stainless steel remain high at elevated temperatures. Therefore, the electrode force required to make the weld is much higher than that required for welding carbon steel. Large electrode force is needed to forge the weld, and thus to minimize cracks and voids in the weld nugget. The increased electrode force requires that the welding current be decreased, particularly in metal of greater thickness, because of the decrease in contact resistance. With an electrode force that is adequate for a given work-metal thickness, insufficient welding current can result in an undersize nugget, whereas excessive welding current can cause excessive indentation.

Spot Spacing. The shunting effect from one spot to another is somewhat less in welding stainless steel than in welding carbon steel, because of the lower electrical conductivity of stainless steel. Therefore, spots can be more closely spaced and the contacting overlap can be less than that for carbon steel. Recommended practices for minimum spot spacing and contacting overlap are given in Table 2.

Spot welding electrodes for stainless steel are about the same size as those used for welding carbon steel, but because the electrode force is greater for stainless, the unit pressure at the electrode face is greater. Therefore, the electrode can be made of a harder material than that used for spot welding carbon steel.

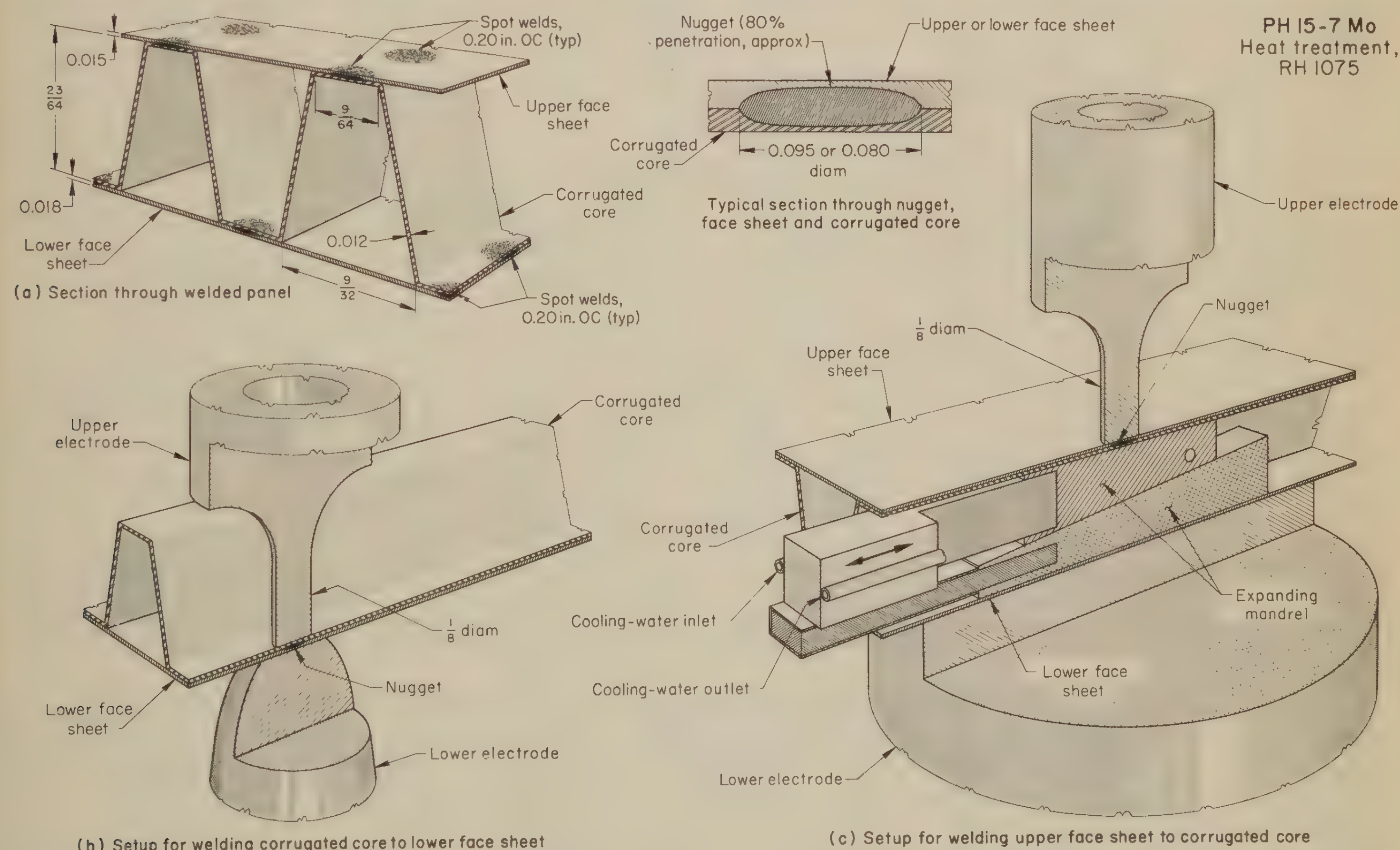
Current requirements generally are low and, consequently, an electrode material with reduced electrical conductivity is permissible. RWMA class 2 and class 3 materials (copper alloys) are generally recommended, but for some applications the refractory metals (classes 10 to 14) can be used. (See Table 2 on page 409 for compositions and properties of electrode materials of classes 2 and 3, and Table 3 on that page for similar information on electrode materials of classes 10 to 14.)

Electrodes of both standard and special designs are used for spot welding stainless steel. In the following example, both the standard and special electrodes were made of a material having high hardness and strength.

Example 409. Resistance Spot Welding of Face Sheets to a Corrugated Core, Using Specially Designed Electrodes (Fig. 2)

A honeycomb panel, 15 in. square, was fabricated by spot welding a 0.012-in.-thick corrugated core to lower and upper face sheets as shown in Fig. 2(a). Before being spot welded, the components of the panel, all of which were made of PH 15-7 Mo stainless steel, were cut to size and the core was corrugated by forming. The components were then heat treated to the RH 1075 condition and chemically cleaned.

The corrugated core was spot welded to the lower face sheet with ⅝-in.-diam electrodes made of RWMA class 3 material. The upper electrode was modified as shown



Conditions for Resistance Spot Welding of Lower Face Sheet to Core

Upper electrode ...Type C, ⅝-in. diam, modified
Lower electrode ....Type A, ⅝-in. diam, ¼-in.-diam tip
Transformer connection ....Series
Weld-heat setting 65%
Postheat setting 20%
Squeeze time ....21 cycles
Weld time ....3 cycles
Hold time ....21 cycles
Postheat time ....3 cycles
Cool time ....2 cycles
Weld impulses ....One
Postheat impulses ....Two
Nugget diameter ....0.080 in.
Production rate ....700 welds per hour

Conditions for Resistance Spot Welding of Upper Face Sheet to Core

Upper electrode ..Type C, ⅝-in. diam, modified
Lower electrode ....(a)
Transformer connection ....Parallel
Weld-heat setting 33%
Postheat setting 10%
Squeeze time ....31 cycles
Weld time ....2 cycles
Hold time ....31 cycles
Postheat time ....3 cycles
Cool time ....1 cycle
Weld impulses ....One
Postheat impulses ....Two
Nugget diameter ....0.095 in.
Production rate ....400 welds per hour

(a) Water-cooled expanding mandrel with 2¼-in.-diam flat-face current-carrying support.

For welding both joints, power supply was 440 v, three phase, 60 cycle; the welding machine was a semiautomatic press type with a series-parallel transformer; welding controls were synchronous, with phase-shift heat control; electrode material was RWMA class 3; electrode force was 350 lb; and weld spacing was five spots per inch.

Fig. 2. Section through a welded honeycomb panel, and setups for resistance spot welding the corrugated core to lower and upper face sheets using specially designed electrodes as shown (Example 409)

in Fig. 2(b) to fit into the corrugation. The lower electrode was of the standard RWMA type A design (pointed face).

The upper face sheet was spot welded to the core using the same modified upper electrode and an expanding mandrel (made of RWMA class 3 material) that was inserted inside the corrugation to serve as an electrode, as shown in Fig. 2(c). The upper portion of the mandrel (1 in. long) was automatically actuated by an air cylinder controlled by the spot welding timer. Up to 100,000 welds were made before the upper portion of the mandrel was replaced. Spot welding progressed along each corrugation from the center of the panel toward each edge; the mandrel was inserted in the corrugation from each edge of the panel.

The lower portion of the mandrel (1½ in. long) was attached to and insulated from the lower platen of the welding machine. A 2¼-in.-diam lower electrode supported the mandrel, and reduced the current density at the contact point between the lower electrode and the lower face sheet so that a weld would be made at the interface between the upper face sheet and the corrugated core. The top half of the mandrel was water cooled, and a filter was needed to prevent dirt particles from clogging the small tube. The two halves of the tapered mandrel were connected to high-strength steel force rods by brazing.

Table 2. Recommended Practices for Resistance Spot Welding of Series 300 Austenitic Stainless Steels (a)

Thickness (t) of thinnest outside piece, in. (b)	Electrode dimensions (c): Body diameter (min), in.	Electrode dimensions (c): Face diameter (max), in.	Net electrode force, lb	Weld time (single impulse), cycles (60 Hz)	Welding current (approx), amp, for work metal with tensile strength of: Less than 150,000 psi	Welding current: 150,000 psi and above	Minimum contacting overlap, in.	Minimum spot spacing (center to center), in. (d)	Nugget diameter (approx), in.	Minimum breaking load of weld in shear, lb, for work metal with tensile strength of: 70,000 to 90,000 psi	90,000 to 150,000 psi	150,000 psi and above
0.006	3/16	3/32	180	2	2,000	2,000	3/16	3/16	0.045	60	70	85
0.008	3/16	3/32	200	3	2,000	2,000	3/16	3/16	0.055	100	130	145
0.010	3/16	1/8	230	3	2,000	2,000	3/16	3/16	0.065	150	170	210
0.012	1/4	1/8	260	3	2,100	2,000	1/4	1/4	0.076	185	210	250
0.014	1/4	1/8	300	4	2,500	2,200	1/4	1/4	0.082	240	250	320
0.016	1/4	1/8	330	4	3,000	2,500	1/4	5/16	0.088	280	300	380
0.018	1/4	1/8	380	4	3,500	2,800	1/4	5/16	0.093	320	360	470
0.021	1/4	5/32	400	4	4,000	3,200	5/16	5/16	0.100	370	470	500
0.025	3/8	5/32	520	5	5,000	4,100	3/8	7/16	0.120	500	600	680
0.031	3/8	3/16	650	5	6,000	4,800	3/8	1/2	0.130	680	800	930
0.034	3/8	3/16	750	6	7,000	5,500	7/16	9/16	0.150	800	920	1100
0.040	3/8	3/16	900	6	7,800	6,300	7/16	5/8	0.160	1000	1270	1400
0.044	3/8	3/16	1000	8	8,700	7,000	7/16	11/16	0.180	1200	1450	1700
0.050	1/2	1/4	1200	8	9,500	7,500	1/2	3/4	0.190	1450	1700	2000
0.056	1/2	1/4	1350	10	10,300	8,300	9/16	7/8	0.210	1700	2000	2450
0.062	1/2	1/4	1500	10	11,000	9,000	5/8	1	0.220	1950	2400	2900
0.070	5/8	1/4	1700	12	12,300	10,000	5/8	1 1/8	0.250	2400	2800	3550
0.078	5/8	5/16	1900	14	14,000	11,000	11/16	1 1/4	0.275	2700	3400	4000
0.094	5/8	5/16	2400	16	15,700	12,700	3/4	1 3/8	0.285	3550	4200	5300
0.109	3/4	3/8	2800	18	17,700	14,000	13/16	1 1/2	0.290	4200	5000	6400
0.125	3/4	3/8	3300	20	18,000	15,500	7/8	2	0.300	5000	6000	7600

SOURCE: "Recommended Practices for Resistance Welding", AWS C1.1; also, "Welding Handbook", 6th Ed., Section 2, American Welding Society, 1969. Published here by permission.

(a) Steel should be free from scale, oxide, paint, grease and oil. (b) Welding conditions are determined by thickness (t) of thinnest outside piece. Data are for total thickness of pile-up not exceeding 4t. Maximum ratio between two thicknesses, 3 to 1. (c) Body diameters apply to electrodes with types A, D and E faces with the face diameters listed, and to type F electrodes with 3-in. spherical-radius faces. Electrode material, RWMA class 2, class 3 or class 11. (d) Minimum spot spacing for two pieces is that spacing for which no special precautions need be taken to compensate for shunting of current through adjacent spot welds. For three pieces, increase spacing 30%.

Table 3. Recommended Practices for Multiple-Impulse Resistance Spot Welding of Series 300 Austenitic Stainless Steels (a)

Thickness (t) of thinnest outside piece, in. (b)	Electrode dimensions (c): Body diameter (min), in.	Electrode dimensions (c): Face diameter (max), in.	Net electrode force, lb	Weld time, pulsations at 15 cycles on, 6 cycles off (60 Hz)	Welding current (approx), amp, for work metal with tensile strength of: Less than 150,000 psi	Welding current: 150,000 psi and above	Minimum contacting overlap, in.	Minimum spot spacing (center to center), in. (d)	Nugget diameter (min), in.	Minimum breaking load of weld in shear, lb, for work metal with tensile strength of: 90,000 to 150,000 psi	150,000 psi and above
0.156	1	1/2	4000	4	20,700	17,500	1 1/4	1 7/8	0.440	7,600	10,000
0.187	1	1/2	5000	5	21,500	18,500	1 1/2	2	0.500	9,750	12,300
0.203	1	5/8	5500	6	22,000	19,000	1 5/8	2 1/8	0.530	10,600	13,000
0.250	1	5/8	7000	7	22,500	20,000	1 3/4	2 3/8	0.600	13,500	17,000

(a) Steel should be free from scale, oxide, paint, grease and oil. (b) Welding conditions are determined by thickness (t) of thinnest outside piece. Data are for total thickness of pile-up not exceeding 4t. Maximum ratio between two thicknesses, 3 to 1. (c) Body diameters apply to electrodes with types A, D and E faces with the face diameters listed, and to type F electrodes with 3-in. spherical-radius faces. Electrode material, class 2 or class 3. (d) Minimum spot spacing for two pieces is that spacing for which no special precautions need be taken to compensate for shunting of current through adjacent spot welds. For three pieces, increase spacing 30%. [SOURCE: Same as Table 2.]

Table 4. Recommended Practices for Resistance Seam Welding of Series 300 Austenitic Stainless Steels (a)

Thickness (t) of thinnest outside piece, in. (b)	Electrode-wheel width (min), in. (c)	Net electrode force, lb	On time, cycles (60 Hz)	Off time, cycles (60 Hz), for obtaining pressure-tight joints at maximum welding speed for total pile-up thickness of: 2t	4t	Maximum welding speed, in. per minute, for total pile-up thickness of: 2t	4t	Welds per inch for total pile-up thickness of: 2t	4t	Welding current (approx), amp	Minimum contacting overlap, in. (d)
0.006	3/16	300	2	1	1	60	67	20	18	4,000	1/4
0.008	3/16	350	2	1	2	67	56	18	16	4,600	1/4
0.010	3/16	400	3	2	2	45	51	16	14	5,000	1/4
0.012	1/4	450	3	2	2	48	55	15	13	5,600	5/16
0.014	1/4	500	3	2	3	51	46	14	13	6,200	5/16
0.016	1/4	600	3	2	3	51	50	14	12	6,700	5/16
0.018	1/4	650	3	2	3	55	50	13	12	7,300	5/16
0.021	1/4	700	3	2	3	55	55	13	11	7,900	3/8
0.025	3/8	850	3	3	4	50	47	12	11	9,200	7/16
0.031	3/8	1000	3	3	4	50	47	12	11	10,600	7/16
0.040	3/8	1300	3	4	5	47	45	11	10	13,000	1/2
0.050	1/2	1600	4	4	5	45	44	10	9	14,200	5/8
0.062	1/2	1850	4	5	7	40	41	10	8	15,100	5/8
0.070	5/8	2150	4	5	7	44	41	9	8	15,900	11/16
0.078	5/8	2300	4	6	7	40	41	9	8	16,500	11/16
0.094	5/8	2550	5	6	7	36	38	9	8	16,600	3/4
0.109	3/4	2950	5	7	9	38	37	8	7	16,800	13/16
0.125	3/4	3300	6	6	8	38	37	8	7	17,000	7/8

(a) Steel should be free from scale, oxide, paint, grease and oil. (b) Welding conditions are determined by thickness (t) of thinnest outside piece. Data are for total thickness of pile-up not exceeding 4t. Maximum ratio between two thicknesses, 3 to 1. (c) Electrode material, RWMA class 3. Face radius, 3 in. (d) For large assemblies, the values listed should be increased 30%. [SOURCE: Same as Table 2.]

The sequence of operations for welding the upper face sheet to the corrugated core was as follows (steps 3 through 5 were automatically controlled in sequence):

1 Place mandrel in the corrugation (twice for each corrugation) and rest on lower electrode.
2 Depress foot switch.
3 Expand mandrel; lower the upper electrode.
4 Make spot weld and postheat.
5 Raise upper electrode; release mandrel.
6 Relocate panel for next spot weld and repeat steps 2 through 5.

All spot welds were made by single-impulse welding under conditions listed in the table with Fig. 2. After the welds had cooled, they were given a double-impulse postheat cycle that was applied before the electrodes were removed.

Effect of Heat Distortion. Because the coefficient of thermal expansion of austenitic stainless steel is considerably higher than that of carbon steel, expansion and contraction of the heated metal should be considered. When metal is heated and cooled rapidly in resistance welding, there is an upsetting action, followed by shrinkage of the metal in the weld zone. This can cause waviness in sheets and, when long welds are made, an over-all shrinkage of the part.

In spot welding, weld shrinkage can be reduced by decreasing the size of the individual welds in the joint. The safe upper limit for spot-weld diameter is four to five times the thickness of the thinnest sheet being welded. If more spots of smaller diameter are used, in such a way that the total volume of weld metal is the same, distortion will be less.

Adequate water cooling will also help in controlling heat distortion.

Expulsion of molten metal, by arcing or flashing during spot welding, can be caused by using high welding current, low electrode pressure, and small area of contact at the interface of the two workpieces. The small area of contact generally is the result of using sharply domed electrodes or too small a face radius. A copious supply of water around the electrodes, both upper and lower, can minimize flashing and allow wider ranges of usable welding current and electrode pressure.

Multiple-Impulse Resistance Spot Welding

Multiple-impulse resistance spot welding consists of transmitting two or more impulses of welding current without removing the electrode force. One purpose of multiple-impulse spot welding is to add a given amount of heat to the weld with minimum damage to the electrodes. The effects of excessive heat on the heat-sensitive grades of stainless steel are avoided; decreased thermal distortion and a reduced amount of harmful carbide precipitation result. Multiple-impulse spot welding is useful for joining austenitic stainless steels in thicknesses greater than ⅛ in.

Recommended practices for multiple-impulse spot welding of austenitic stainless steels are given in Table 3. Impulses are shorter and fewer, welding current is slightly greater, and electrode force is much greater, than for multiple-impulse spot welding of carbon steels with comparable thicknesses.

Table 5. Continuous Resistance Seam Welding of Three Assemblies Made From Mill-Pickled Stainless Steel Sheets of Dissimilar Thicknesses (Examples 410, 411 and 412)

Item	Example 410	Example 411	Example 412
Details of Sheets Welded			
Upper sheet (alloy and thickness, in.)	Type 310, 0.050	Type 316, 0.062	Type 316, 0.093
Lower sheet (alloy and thickness, in.)	Type 310, 0.043	Type 316, 0.093	Type 321, 0.062
Overlap of sheets at joint, in.	0.400	1.000	0.508
Equipment Details			
Power supply	Three-phase half-wave frequency converter; 100-kva rating		
Welding machine	Circular, with synchronous controls and phase-shift heat control		
Upper electrode(a):			
Diameter, in.	10	10	14
Face width, in.	0.280	0.375	0.362
Face radius, in.	3	12	5½
Lower electrode(a):			
Diameter, in.	6½	10	10
Face width, in.	0.280	0.375	0.312
Face radius, in.	3	12	6
Welding Conditions			
Welding current and voltage	Three-phase half-wave rectified current; 3 to 6 volts across weld		
Heat setting, %	30	30	30
Electrode force, lb	1500	2200	2200
Squeeze time, cycles(b)	72	36	36
Hold time, cycles(c)	36	36	36
Heat time, cycles	10	12	12
Cool time, cycles	6	16	16
Impulses per spot	1	1	1
Nugget width and height, in.	0.21, 0.048	0.22, 0.078	0.25, 0.078
Spots per inch	14	16	16
Welding speed, in. per minute	16	8	8

(a) Electrode material for all three applications was RWMA class 3. (b) Squeeze time at beginning of seam, before welding had started. (c) Hold time at end of seam, after welding had stopped.

The pulsations can also be used for postheat cycles. Two short impulses were used to postheat the weld in the application described in Example 409.

Resistance Seam Welding and Roll Resistance Spot Welding

Resistance seam welding operates on a time cycle of current on (heat) and current off (cool) while the workpieces are traversed and pressure is exerted on them by rotating electrode wheels, which are in continuous contact with the work metal, to produce a line of overlapping spot welds. The overlapping spot welds provide gastight or liquid-tight seams. The spot welds can be spaced apart, which is known as roll resistance spot welding.

Seam welds are usually made in lap joints, and can be made in a straight line on flat metal, can be carried around corners by using a small electrode wheel on the inside, or can be installed as girth joints between cylinder walls and inserted head flanges. Mash-seam welding can be used to produce flush joints on thin metal.

Roll resistance spot welding is done with the same equipment used for resistance seam welding, and is similar to it except that the spots are not overlapping. The spots can be made at any desired spacing, and the seams are not necessarily gastight or liquid-tight.

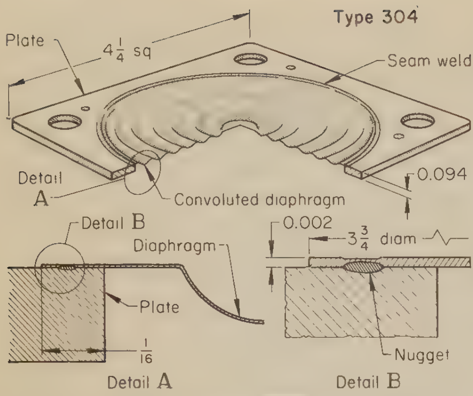
Mash Resistance Seam Welding. Flush joints in stainless steel up to about 0.062 in. thick can be produced by mashing down the double metal thickness of a lap joint to approximately that of one member of the assembly. The operation is made possible by (*a*) reducing the overlap below that ordinarily used for seam welding, (*b*) increasing the electrode pressure, (*c*) decreasing the welding speed, and (*d*) increasing the rate of heat generation in the work metal by eliminating cool time from the weld cycle.

The overlap is a maximum of 1½ times the thickness of one sheet of work metal. The sheets must be assembled carefully before welding and held rigidly during welding. Electrodes are machined to flat faces to straddle the overlap and produce a uniform joint. Electrode pressure has an effect on thickness of the joint and on contact resistance. Square edges are satisfactory on metal thicknesses up to about 0.050 in. On thicker metal, beveling the overlapping edges may be helpful because it reduces the amount of plastic-metal movement needed for thickness control. (See also "Mash Seam Welds" and "Foil Butt Seam Welds", page 433.)

Seam Welding Machines. Seam welding of stainless steel is done with the same machines used for seam welding of carbon steel. Welding pressures are greater and weld time and current are less than in welding carbon steel, but more accurate control over welding conditions is needed.

The annealed austenitic stainless steels are nonmagnetic and do not influence the reactance of the secondary circuit of the welding machine. Therefore, on longitudinal seam welding machines, welding current does not change as the welded assembly is fed into the throat of the machine. However, cold working induces some magnetism in austenitic stainless steels. The martensitic and ferritic grades are ferromagnetic and have a marked effect on the characteristics of the secondary circuit.

Heat Distortion. The installation of a closely spaced succession of spot welds generates considerable heat in the workpieces — a condition that can cause unwanted metallurgical effects or excessive warpage.



Equipment Details

Power supply	220 v, single phase, 60 cycle
Welding machine	Bench mounted, press type
Transformer rating at 50% duty cycle	30 kva
Secondary current, max	15,000 amp
Transformer taps	Four
Electrodes	5½-in. diam, ¾ in. thick at hub, 0.100 in. thick at contact surface
Electrode material	RWMA class 3
Electrode force, max	900 lb
Welding controls	Spike power, synchronous, half-cycle multispot, phase-shift heat control

Conditions for Resistance Seam Welding

Welding current	2000 to 4000 amp
Heat-control setting	No. 3 tap and 50%
Squeeze time(a)	40 cycles
Hold time(a)	40 cycles
Welding speed	20 in. per minute
Spots per inch	8 to 11

(a) Applied at the beginning and end of seam

Fig. 3. Diaphragm-and-plate assembly, and details of joint that was resistance seam welded using close control of welding conditions to minimize distortion (Example 413)

Stainless steels with extra-low carbon content, such as 304L and 316L, or the stabilized compositions (321, 347 and 348) can be used to avoid intergranular carbide precipitation. The best method of controlling thermal distortion on any grade of stainless steel is to prevent excessive heat buildup and absorption during seam welding. Forced cooling of the work metal is commonly done with jets or sprays of water directed on the work at the point of contact with the wheels. The water spray should be directed to the top and bottom of the sheets both before and behind the electrode wheels. A copious flow of water over the electrode wheel is sometimes used. Welding can be done underwater if the size of the workpiece permits.

Welding Schedules. Recommended practices for resistance seam welding of austenitic stainless steels are given in Table 4. Test welds should be made before starting production, to determine optimum conditions, using the conditions listed in Table 4 as starting points. Conditions can be adjusted according to the procedure given on page 428 for setting up a schedule for resistance seam welding.

The wide latitude of conditions under which seam welds can be made between stainless steel sheets of dissimilar thicknesses is illustrated in the group of three examples that follows.

Examples 410 to 412. Conditions for Seam Welding Three Combinations of Stainless Steel Sheets of Dissimilar Thicknesses (Table 5)

Table 5 lists equipment details and welding conditions for continuous seam welding of type 310 sheets 0.050 and 0.043 in. thick (Example 410), type 316 sheets 0.062 and 0.093 in. thick (Example 411), and types 316 and 321 sheets 0.093 and 0.062 in. thick, respectively (Example 412).

For all three applications, the electrode wheels were made of RWMA class 3 material (a low-beryllium copper alloy), to reduce deformation of the contact surface resulting from high heat, long weld time, inadequate cooling and highly concentrated electrode force. The welding machine for the three applications was a circular type. Power was supplied by a three-phase half-wave frequency converter.

The high electrode forces and low welding speeds used for joining these sheets provided consistency in obtaining high-strength, crack-free seam welded joints.

In the following example, the welding procedures and control limits had to be determined experimentally and then followed very carefully, to ensure quality of the seam weld.

Example 413. Control of Current and Electrode Force for Distortion-Free Seam Welding (Fig. 3)

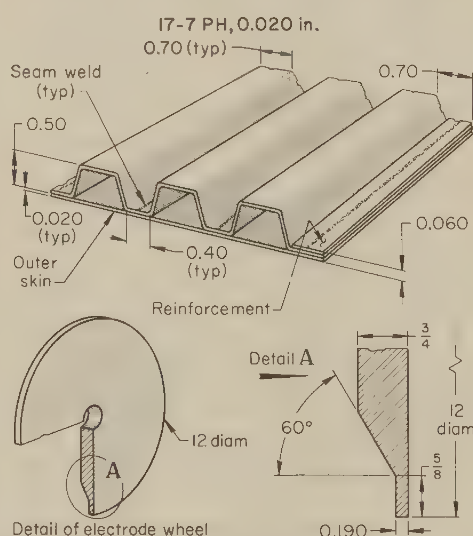
A 0.002-in.-thick diaphragm had to be seam welded to a 0.094-in.-thick plate, as shown in Fig. 3, without causing distortion of the diaphragm or warping of the plate. Overheating could not be tolerated on either component of the assembly (both of which were made of type 304 stainless steel), and the completed joint had to withstand an air pressure of 50 psi under water without leaking.

Welding was done in a manually operated, bench-mounted, press-type welding machine, using a 30-kva single-phase transformer. The machine had spike-power welding controls and could weld a seam up to ⅛ in. wide. Maximum power per spike was achieved in 4.5 millisec. Electrode force was supplied by a 3-in.-diam air cylinder. Originally, the weld width was greater than 1⁄16 in., to permit formation of a nugget at the outside edge of the diaphragm. The electrode wheel could not extend into the hole spanned by the diaphragm, because welds in that area would result in cracks and cutting of the diaphragm.

After preliminary production, the following modifications were incorporated in the welding machine:

1. The machine cycle was changed from continuous to multispot welding.
2. The upper arm of the machine was rebuilt to move the centerline of the electrode wheel outward, and the welding head was counterbalanced by means of springs to provide low inertia.
3. Guide supports were added to the ram to improve alignment of the welding head.
4. Air pressure to the air cylinder that provided the electrode force was adjusted to obtain proper electrode pressure and contact resistance.
5. Weld width was reduced to under 1⁄16 in.

With the above changes, the rejection rate was reduced to 10%, which was a considerable improvement over the 50% rejection rate obtained when welding was done by a subcontractor using three-phase equipment, and the 60% rejection rate obtained in in-plant welding before modification of the machine. Equipment details and welding conditions for the revised procedure are given in the table with Fig. 3.



Equipment Details

Power supply	440 v, three phase, 60 cycle
Welding machine	Circular
Transformer rating at 50% duty cycle	50 kva
Electrodes	12-in. diam, ¾ in. thick, with 0.190-in.-wide flat contact surfaces
Electrode material	RWMA class 3
Electrode force, max	4000 lb
Welding controls	Synchronous, with phase-shift heat control

Resistance Seam Welding Conditions	Two sheet thicknesses	Three sheet thicknesses
Heat-control setting	28%	46%
Electrode force, lb	800	800
Squeeze time, cycles	30	30
Heat time, cycles	2	2
Cool time, cycles	3	4
Hold time, cycles	30	30
Seam width, in.	0.170	0.150
Weld penetration, %	48	42
Welding speed, ipm	44	44
Spots per inch	16 to 17	14 to 15

Fig. 4. Aircraft-fuselage blast panel that was resistance seam welded with electrodes having flat contact surfaces as shown (Example 414)

Electrode wheels for resistance seam welding of stainless steel are often made of RWMA class 3 material in order to withstand high electrode forces. With softer electrode materials, mushrooming of the contact face occurs and weld quality is reduced.

The shape of the contact face on an electrode wheel can have a marked effect on the life of the wheel and on the size of the weld nuggets. In the following example, radius-face wheels were replaced by flat-face wheels because the radius rapidly flattened and thus caused nugget width to increase and penetration to decrease.

Example 414. Effect of Electrode-Wheel Design on Electrode Maintenance and Size of Weld Nugget in Resistance Seam Welding (Fig. 4)

Blast panels (24 by 14 in.) for the tail section of the fuselage of a jet aircraft were fabricated by resistance seam welding a corrugated member to an outer skin as shown in Fig. 4. Both components of the assembly were made of 0.020-in.-thick 17-7 PH stainless steel (annealed). A reinforcing strip of the same material and thickness was added to one edge of the panel, necessitating seam welding three sheet thicknesses along that edge.

Originally, welding was done with 12-in.-diam electrode wheels that had 10-in.-radius contact faces. The contact faces were 0.190 in. in width. However, inaccuracies in dressing the contact faces resulted in surfaces with radii varying from 9 to 11 in. Also, after the wheel had been in use for a short time, wear produced a flat on the radiused contact face, and this resulted in changes in the size of the weld nuggets (increased width and decreased penetration).

By changing from radius-face wheels to flat-face (0.190 in. wide) wheels of the design shown in Fig. 4, wheel life between dressings was increased and weld size was more uniform. The flat-face wheels were dressed after 16 to 24 hours of production. To establish the need for remachining the faces of the wheels and to determine weld quality, test samples were taken hourly and at the beginning and end of each shift. The nuggets were sectioned both longitudinally

and transversely so that weld penetration and nugget size could be measured.

Before being seam welded, the components of the panel were tack spot welded at intervals of 3 to 4 in. The assembly was held at the approximate final contour during tack welding by means of a lightweight laminated fiber-glass fixture. Seam welding was done without the use of fixtures, under the conditions listed in the table with Fig. 4. Initially, speed in seam welding had been 30 ipm; later, speed was increased to 44 ipm, which was established as the practical maximum for this application. Higher speeds made it difficult to guide the panels through the seam welding machine without damaging the components or improperly locating the seam.

Seam Welding vs Induction Brazing. The short weld impulses used in seam welding produce a gastight joint while introducing a minimum of heat into the work metal. Brazing usually requires that the components being joined be heated over a larger area to achieve correct flow of filler metal and proper bonding. The following example describes an application in which induction brazing was replaced by seam welding because brazing did not consistently produce gastight joints.

Example 415. Change From Induction Brazing to Resistance Seam Welding, To Obtain Flux-Free, Gastight Joints (Fig. 5)

The end closure of a solenoid-valve assembly was originally made by induction silver brazing a type 430F stainless steel plug to the end of a type 321 stainless steel tube as shown at upper right in Fig. 5. The tube contained the components of the solenoid valve, including a 17-7 PH stainless steel spring and a brass sleeve-type spacer, about ⅛ in. long, which separated the plug from the spring. Because of the spring, it was important that the assembly be heated rapidly (without overheating) and cooled immediately. The end of the plug was inserted a short distance into the tube to retain the brazing filler metal. The plug had a V-groove that served as a flux trap, and the tube was staked into the groove at four places for longitudinal location.

Brazing did not consistently produce gastight joints, and necessitated cleaning of the outer surfaces of the tubes. Also, there was no assurance that some flux would not be retained inside the tube when the assembly was joined by brazing.

A change was made to resistance seam welding using a special seam welding machine with two flat-face electrode wheels that rotated in the same direction. The tube, which was inserted between the electrode wheels (Fig. 5, upper left), was held in a rotatable fixture. The electrode wheels were driven at their periphery, to maintain a constant peripheral speed regardless of reduction in diameter resulting from wear and re-dressing. The tube was rotated slightly more than 180°, and the assembly was welded in about 1½ seconds. Equipment details and welding conditions are given in the table that accompanies Fig. 5. Welding by this procedure was possible only because the tube wall was very thin in relation to the diameter of the plug.

Production rate in resistance seam welding was 640 assemblies per hour, which was about 2½ times the production rate obtained in brazing. Leakage was reduced by 67%. Because no flux was used, there was no need to clean the finished assembly, and no possibility of flux contamination inside the assembly.

The welded assemblies were leak tested using a mixture of refrigerant gas (dichlorodifluoromethane) and air at 400 psi. The testing unit consisted of a halide detector that was capable of detecting leaks greater than 10^{-6} cu cm per second when measured under standard conditions of one atmosphere at 70 F.

Projection Welding

Projection welding offers advantages in the fabrication of stainless steel similar to those obtainable in welding carbon steel. The current and electrode force are concentrated at well-defined spot areas in projection welding, which minimizes the adverse effects of excessive heat on the more heat-sensitive grades. Such effects are characteristic of spot welding, in which contact areas are larger. Also, in projection welding, shunting effects of surface irregularities are eliminated and areas of contact at individual points are constant.

The same projection designs and methods of forming are used for stainless steel as for carbon steel. When three or more projections are welded simultaneously, variations in diameter, contour, and height of the projections can result in variation in current density, and thus weld quality. When components are of different thicknesses, projections should be in the thicker piece to maintain better heat balance.

Projection welding design data for stainless steel are given in Table 2, page 440, in the article on Projection Welding in this volume.

Example 408 in the present article gives data on projection welding of type 440A to type 430 stainless steel.

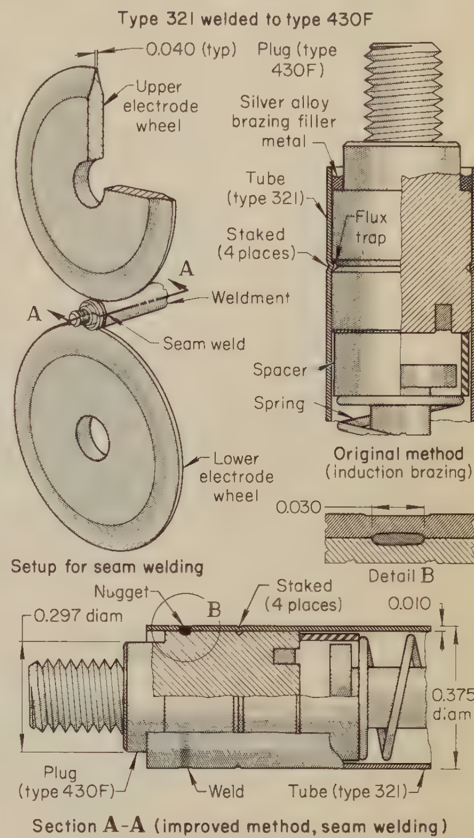
Welding Schedules. Recommended practices for projection welding of austenitic stainless steels are given in Table 6; the values listed there may require adjustment to suit the requirements of individual applications.

Projection Welding vs Torch Brazing. Projection welding can be done without marring one surface of the assembly, and this makes it competitive with brazing for fabrication of assemblies in which appearance is an important factor, as in the following example.

Example 416. Projection Welding vs Torch Brazing for Mark-Free Surfaces (Fig. 6)

A cover plate and a bracket were joined by resistance projection welding using a specially designed fixture, as shown in Fig. 6. Specifications required the bracket to be perpendicular to the surface of the cover plate within a tolerance of ±1°. The components of the assembly, which were made of 0.036-in.-thick type 302 stainless steel, had been designed originally for torch brazing, because the cover plate was a decorative part and was required to be free of weld marks on its outer surface. Resistance spot welding was not considered, because it would have left weld marks.

Brazing was done with AWS No. 3 flux and BAg-1 filler wire, using an oxyacetylene torch having a 0.030-in.-diam hole at the tip. Brazed assemblies, however, were unacceptable because of thermal distortion.



Equipment Details

Power supply ......230 v, single phase, 60 cycle
Welding machine ....Circular
Transformer rating at 50% duty cycle ...30 kva
Transformer taps ....Eight
Electrodes .....5-in. diam; ⅜ in. thick at hub; 0.04 in. thick at contact surface
Electrode material ....RWMA class 2
Electrode force, max ....150 lb
Welding controls ....Synchronous, with phase-shift heat control

Conditions for Resistance Seam Welding

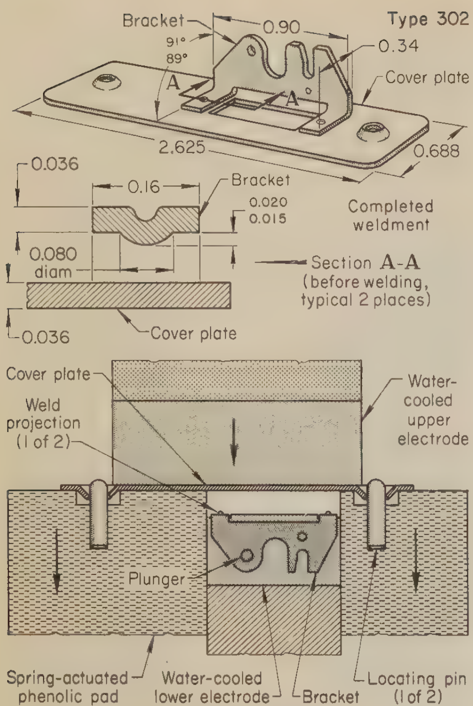
Heat-control setting ....No. 7 tap and 90%
Electrode force ....118 lb
Squeeze time ....20 cycles
Heat time ....3 cycles
Cool time ....1 cycle
Spots per inch ....25 to 27
Production rate ....640 assemblies per hour

Fig. 5. Tube-and-plug assembly for which induction silver brazing was replaced by resistance seam welding, to obtain gastight joints (Example 415)

Table 6. Recommended Practices for Projection Welding of Series 300 Stainless Steels (a)

Thickness (t) of thinner piece (nominal), in.(b)	Electrode face diameter, in.(c)	Net electrode force, lb	Weld time, cycles (60 Hz)	Hold time, cycles (60 Hz)	Welding current at electrodes (approx), amp (60-Hz ac)
0.014	⅛	300	7	15	4,500
0.021	5⁄32	500	10	15	4,750
0.031	3⁄16	700	15	15	5,750
0.044	¼	700	20	15	6,000
0.062	5⁄16	1200	25	15	7,500
0.078	⅜	1900	30	30	10,000
0.094	7⁄16	1900	30	30	10,000
0.109	½	2800	30	45	13,000
0.125	9⁄16	2800	30	45	14,000

(a) Steel should be free from scale, oxide, paint, grease and oil. (b) Welding conditions are based on thickness (*t*) of thinner piece, and for two thicknesses only. Maximum ratio between two thicknesses, 3 to 1. (c) Electrode face diameter is equal to twice the diameter of the projection. Electrode material, RWMA class 2 or class 12. See Table 2 in the article on Projection Welding for design of standard projections. Conditions for projection welding other thicknesses shown in that table are not yet available. [Source of table: Same as Table 2.]



Equipment Details

Power supply	220 v, single phase, 60 cycle
Welding machine	Press-type spot and projection
Transformer rating at 50% duty cycle	30 kva
Secondary current, max	18,250 amp
Secondary voltage, max	8 v
Transformer taps	Eight
Upper electrode	⅝ by ⅝ by 2 in., RWMA class 11
Lower electrode	½ by ½ by 1 in., RWMA class 2
Electrode force, max	1000 lb
Welding controls	Synchronous, with phase-shift heat control

Conditions for Projection Welding

Welding current	3750 amp, ac
Welding voltage	5.39 v
Heat-control setting	No. 3 tap and 76%
Electrode force	135 lb
Squeeze time	10 cycles
Weld time	9 cycles
Hold time	20 cycles
Production per hour	300 assemblies (600 welds)

Fig. 6. Cover plate and bracket that were projection welded in the fixture shown, to obtain a combination of close alignment, blemish-free appearance and high production rate (Example 416)

and because flux and brazing alloy flowed to the upper surface of the cover plate regardless of the brazing techniques or fixture design used. Moreover, the pits formed by the flux could not be removed by electropolishing and could be removed only by wheel buffing. Also, the production rate achieved by brazing was only 95 assemblies per hour; rejection rate was about 25%.

By changing from brazing to projection welding, the production rate was increased from 95 to 300 assemblies per hour, and rejection rate was reduced to less than 1%. Projection welding was accomplished by using a fixture (see lower view in Fig. 6) to maintain the desired squareness and alignment between the cover plate and the bracket. The bracket was placed on the stationary lower electrode and held in place with a spring-loaded plunger that passed through the large round hole of the bracket. The cover plate was placed in position on locating pins resting on a spring-actuated phenolic pad that was guided by four leader pins (not shown in Fig. 6).

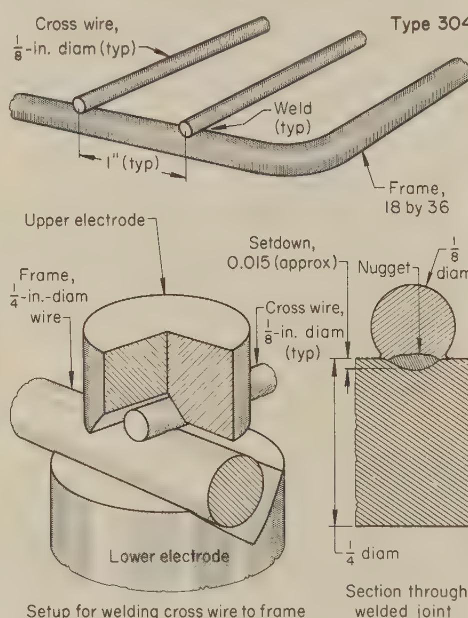
When the upper electrode was lowered, the cover plate was clamped to the phenolic pad and was brought to bear on the weld projections that were formed on the angle-shape bracket. With the components thus aligned and clamped in position, welding current was initiated to make the projection welds. Equipment details and welding conditions are given in the table that accompanies Fig. 6. After being welded, the assembly was removed manually and visually inspected.

To ensure a blemish-free cover plate, the welding electrodes were water cooled. The upper electrode was ground and polished to protect the polished finish on the cover plate. Also, the surfaces of the electrodes were kept parallel within 0.002 in. The upper electrode was dressed after welding an average of 5000 assemblies.

Cross-Wire Welding

Cross-wire welding is a form of projection welding in which the curved surfaces of the wires form the projected or localized areas for the welds.

Conventional press-type resistance welding machines are used for cross-wire welding. Cross-wire resistance welds can be made singly or in multiples, as permitted by part design and the availability of suitable welding machines. Flat-face (RWMA type C) spot welding electrodes or electrodes with a V-groove across the face are used for single welds. Flat bar-type electrodes are used for multiple welds. Cut and formed wire sections are generally held in fixtures during welding.



Equipment Details

Power supply	440 v, single phase, 60 cycle
Welding machine	Press type spot, semiautomatic
Rating at 50% duty cycle	60 kva
Secondary current, max	70,000 amp
Secondary voltage, max	3 v
Transformer taps	Eight
Upper electrode	⅝-in. diam (grooved face)
Lower electrode	¾-in. diam (grooved face)
Electrode material	RWMA class 2
Electrode force, max	3000 lb
Welding controls	Synchronous, with phase-shift heat control

Conditions for Cross-Wire Welding

Welding current	3000 amp, ac
Welding voltage	1 v
Heat-control setting	No. 1 tap and 50%
Electrode force	350 lb
Squeeze time	10 cycles
Weld time	4 cycles
Hold time	10 cycles
Production per hour	20 assemblies

Fig. 7. Cross-wire welding of a food-handling tray, in which low setdown provided adequate strength while minimizing flash and discoloration (Example 417)

The strength of cross-wire welds in types 304 and 430 stainless steels is about the same. However, the austenitic stainless steels provide a sounder and a more dependable welded joint. Weld strength is a function of the setdown of the wires at the joint, and is not affected by any temper in the wire resulting from cold drawing. Maximum strength is achieved in all wire sizes at about 30% setdown. (Percentage of setdown is determined by dividing the setdown, which represents the difference in the combined height of the two wires before and after welding, by the diameter of the smaller wire, and multiplying the result by 100.) Best appearance and avoidance of excess flash from the joint are obtained with about 20% setdown, but lower weld strength is obtained with 20% setdown than with 30% setdown. The optimum electrode force, and tensile breaking-load values for 20% and 30% setdown, for cross-wire welding of three sizes of type 304 wire are given in Table 7.

In cross-wire welding, electrode force is related to wire diameter. Weld time and welding current control the amount of setdown, flash and discoloration. For the application in the following example, strength and appearance were the criteria used for selecting the welding conditions.

Example 417. Cross-Wire Welding of Stainless Steel Trays (Fig. 7)

Food-handling trays measuring 18 by 36 in. were designed for fabrication by cross-wire welding. The trays, consisting of a frame made of ¼-in.-diam type 304 stainless steel wire and ⅛-in.-diam cross wires of the same material, were set up for welding as shown in Fig. 7. Welding was done with the wires held in position by means of a fixture. Equipment details and welding conditions are given in the table that accompanies Fig. 7.

The 350-lb electrode force was selected on the basis of the smaller (⅛-in.-diam) wire. The short weld time (4 cycles) was selected to avoid discoloration. The 3000-amp welding current was selected to produce a setdown of only 0.015 in. (12% setdown) — which provided adequate strength for the application. The small amount of setdown resulted in negligible flash and also helped to avoid discoloration. As a result, bright finishing of the as-welded trays was easily accomplished by electropolishing.

Welding Dissimilar Metals

In resistance welding of stainless steel to another metal, the maximum electrical resistance may not be at the interface of the two workpieces, but within the stainless steel workpiece, because of its high electrical resistivity. The low thermal conductivity of the stainless steel can result in a greater heat loss in the weld zone of the other work metal because heat is conducted away more rapidly than in the weld zone of the stainless steel workpiece.

The low electrical conductivity of stainless steel reduces the shunting effect from one spot to another. However, in resistance welding stainless steel to another metal, the heat and follow-up of the electrode must be carefully controlled. Too little heat does not give enough penetration in

the stainless steel to produce adequate weld strength, and too much heat can cause identation and expulsion of the other metal at spots close to the edge of the joint.

In the following example, an austenitic stainless steel was spot welded to a copper alloy. The welding conditions were carefully controlled; adequate electrode force and a low-inertia welding head with fast follow-up were needed to prevent cracking in the stainless steel.

Example 418. Control of Heat and Electrode Follow-up in Spot Welding a Flat Phosphor Bronze Spring to a Stainless Steel Strip in a Hem-Type Joint (Fig. 8)

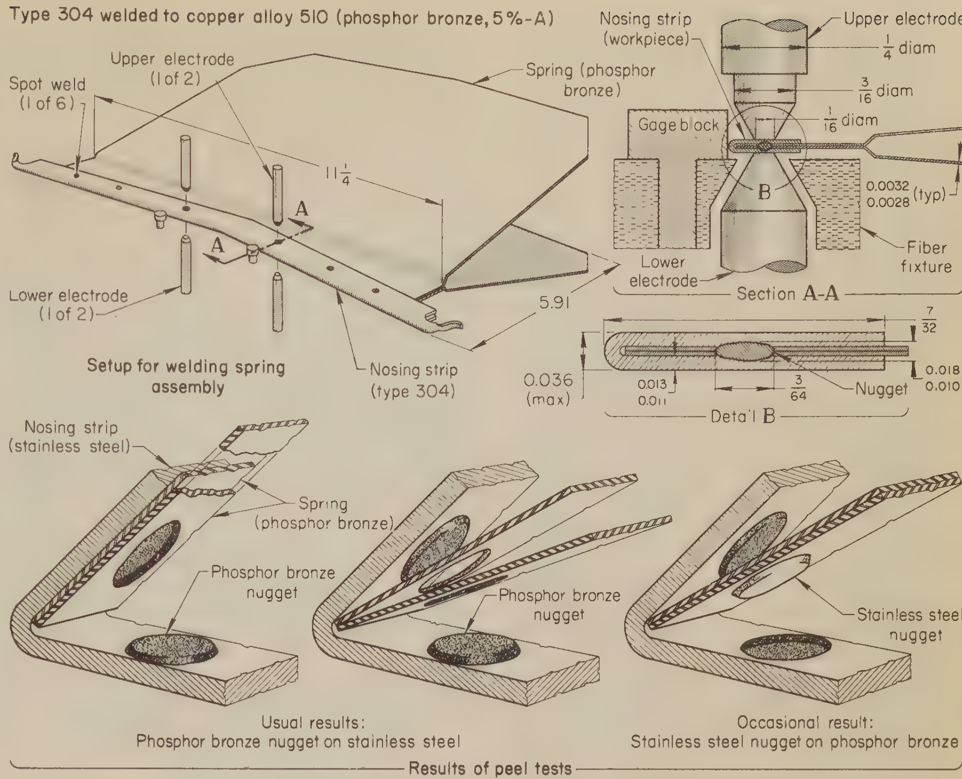
The spring assembly shown in Fig. 8 (upper left) was used in an electronic memory unit, to provide uniform pressure for holding a magnet card against its magnetizing plane. The flat ends of the two halves of the spring, which was made of 0.003-in.-thick phosphor bronze (copper alloy 510) foil, were sandwiched between a U-shape nosing strip of 0.012-in.-thick type 304 stainless steel, and the assembly was joined by means of six spot welds. The design of the joint avoided burn-through, which is often encountered in welding such thin metal in the usual sheet-to-sheet arrangement. The stainless steel strip, which was primarily intended to provide structural strength, also served as a connection for electrical grounding.

The welded assembly was required to be of uniform thickness (0.036 in. max), except for a slight depression in the nosing strip at each bearing point of an electrode. The presence of waviness and weld spatter were unacceptable.

A press-type semiautomatic spot welding machine was used that had a head with a low-inertia inner-shaft assembly capable of providing fast follow-up. Holders for the two upper electrodes were mounted to the inner shaft, and holders for the two opposing lower electrodes were mounted on the platen. The six spot welds were made, two at a time, by direct welding. Conditions for welding were closely adjusted to the settings given in the table with Fig. 8, to avoid expulsion of the copper alloy and to obtain adequate weld penetration in the stainless steel. Expulsion of the copper alloy was avoided as long as the spots were made with the specified welding current and the correct edge distance. Because stainless steel has higher electrical resistivity at room temperature than does phosphor bronze, only a small percentage of the current was shunted around the nosing strip.

During welding, the assembly was positioned and supported by a fixture made of a nonconducting material and was held against gage blocks in three locations (one for the position of each pair of spot welds). The upper electrode had a portion of its shank reduced to 3/16 in. in diameter to clear the gage blocks (see Fig. 8, upper right). As the welding-machine head was lowered by an air cylinder, deflection of a leaf spring, incorporated in the head and bearing on an inner shaft that carried the electrode holder, provided the actual electrode force. The leaf spring also served as a decoupling device and allowed the low-inertia inner shaft, electrode holder and electrode assembly to follow quickly as the metal in the weld zone softened on reaching welding temperature. The resulting electrode indentation was shallow, and the fast follow-up made sound welds and prevented cracks in the stainless steel at the weld. Deflection of the leaf spring also closed a limit switch to start the welding current. When follow-up was slow and force was insufficient, cracks were visible on the outer surface of the stainless steel and extended through to the phosphor bronze.

In peel tests, which were conducted at regular intervals, the nugget usually was pulled from the phosphor bronze, but occasionally, if the welds were made with higher heat, the nugget was pulled from the stainless steel (Fig. 8, bottom view).



Equipment Details	
Power supply	460 v, single phase, 60 cycle
Welding machine	Press type, semiautomatic
Transformer rating at 50% duty cycle(a)	3 kva
Secondary current & voltage(b)	5400 amp, 6 v
Transformer taps	Ten
Electrodes	RWMA class 2(c)
Electrode force, max	60 lb per electrode
Welding controls	Synchronous, with phase-shift heat control

Conditions for Resistance Spot Welding	
Welding current	2000 amp, ac
Welding voltage	3.25 v
Heat-control setting	No. 4 tap and 70%
Electrode force	50 lb per electrode
Squeeze time	(d)
Weld time	2 cycles
Machine cycle time	1 sec
Hold time	Provided in machine cycle time
Production per hour	200 assemblies(e)

(a) Two transformers, one for each set of electrodes used in making the spot welds two at a time. (b) Maximum. (c) Type E (truncated), 1/4-in. diam, 1 3/4 in. long, 60° chamfer, 1/16-in.-diam face. (d) Not required, because of delay in initiating the welding current. (e) 1200 welds.

Close control of heat was needed to obtain sufficient weld strength and to avoid expulsion of phosphor bronze; a low-inertia, fast-follow-up head was used to prevent weld cracking.

Fig. 8. Assembly consisting of a foil-thin phosphor bronze spring and a stainless steel nosing strip, which was resistance spot welded in the setup shown, and results of peel tests after welding (Example 418)

Nickel-base heat-resisting alloys of both solid-solution and precipitation-hardenable types can be resistance spot welded to austenitic stainless steels by making moderate adjustments in the welding schedules for joining the nickel-base alloys to themselves.

In a study of the resistance welding behavior of the solid-solution alloy Hastelloy X and the precipitation-hardening alloy GMR-235, sound spot welds were produced between 0.090-in.-thick type 321 austenitic stainless steel and 0.063-in.-thick Hastelloy X, and between 0.090-in.-thick type 316 austenitic stainless steel and 0.063-in.-thick GMR-235. Best results were obtained by multiple-impulse spot welding, using high welding current, high electrode force, and long welding time.

Grain-boundary fusion in the nickel-base alloys at the periphery of the weld nugget was minimized by directing a stream of cooling water at the electrodes all during welding.

The spot welding was done on pickled and degreased sheets. The Hastelloy X was in the solution heat treated condition, and the GMR-235 was in the precipitation-hardened condition. Spot welding conditions and test results are given in Table 8. Evaluation of welds consisted of (*a*) macroscopic examination for soundness, penetration, and nugget diameter; (*b*) measurement of shear strength and cross tensile strength; and (*c*) x-ray examination to detect porosity and cracking. Maximum indentation was 10%, and penetration was 50 to 60% — both based on the total thickness of the sheets.

Table 7. Optimum Electrode Force and Tensile Breaking Load for Cross-Wire Welding of Three Sizes of Type 304 Stainless Steel Wire

Wire diameter, in.	Optimum electrode force, lb	Tensile breaking load, lb, for setdown(a) of: 20%	30%
0.125	350	1350	1800
0.156	600	...	3350
0.250	1700	5800	8100

(a) Percentage of setdown is determined by dividing the setdown (difference between the combined height of the two wires before and after welding) by the diameter of the smaller wire, and multiplying the result by 100.

Table 8. Multiple-Impulse Resistance Spot Welding of 0.090-In.-Thick Austenitic Stainless Steels to 0.063-In.-Thick Hastelloy X and GMR-235

Equipment Details and Welding Conditions

Power supply . . 440-v, three-phase, 60-cycle ac
Welding machine . . . . 100-kva air-operated press type, with electronic timing and phase-shift heat control
Electrodes . . Flat, 5⁄16-in. diam; RWMA class 3; internal and external water cooling
Welding current . . . . 26,600 amp
Welding pulsations . . . . 8 impulses, each of 10 cycles heat time plus 2 cycles cool time
Electrode force, lb . . . . Weld, 2000; forge, 4000

Property of weld	Type 321 stainless welded to Hastelloy X	Type 316 stainless welded to GMR-235
Test Results on Spot Welds		
Shear strength, lb(a):		
Average	3574	4050
Minimum	3360	3930
Maximum	3750	4160
Variation from avg	+4% to −6%	+3% to −3%
Min allowable avg(b)	2530	2530
Tensile strength (cross), lb:		
Average	2250	2675
Minimum	1770	2490
Maximum	3010	3050
Tensile strength/shear strength(c)	0.63	0.66
Nugget diam (avg), in.	9⁄32	9⁄32

(a) Beam load. (b) For 0.062-in. sheet thickness, per MIL-W-6858, 90,000-to-150,000-psi class. (c) Based on average values.

Flash Welding

Flash welding is used for butt joining of stainless steel bars, tubing and pipe. Also, it is used for making joints in rings that have been rolled from strip stock, bars and extrusions. The making of type 410 and 17-7 PH stainless steel rings is described in Examples 433, 440 and 450 in the article on Flash Welding, which begins on page 485 in this volume.

Stainless steels can be joined to themselves and to other metals by flash welding. Table 2 in the article on Flash Welding lists metals to which stainless steel has been successfully flash welded.

The flashing-current requirements for welding stainless steel are slightly less than those for welding carbon steel. The upsetting pressures range from 13,000 to 25,000 psi, which are somewhat greater than those needed for carbon steel. Best results are obtained when relatively long flash-off periods and a large amount of upset are used. The clamping pressures used on stainless steel are about 50% greater than those used on carbon steel, because of the high contact resistance of stainless steel and the high upsetting forces needed. A protective atmosphere may be desirable during flashing, to improve the mechanical properties.

Causes and Prevention of Weld Defects

Indentations and discoloration of resistance welds are common weld defects that detract from the appearance of finished welds. Cracks and voids in the weld nugget and cracks in the base metal are also common defects.

Indentations are the result of plastic yielding of base metal under the force of the electrodes at the welding temperature. Improper maintenance of the electrode face, excessive electrode force and welding current, and shrinkage in the weld nugget are common causes.

Heat Tinting. All stainless steels are susceptible to discoloration at temperatures above about 400 F. The oxygen in the atmosphere will cause tinting if the electrode is withdrawn before the metal has cooled sufficiently. To safeguard corrosion resistance in atmospheres that are more than mildly corrosive, and to improve appearance, the work-metal surfaces should be cleaned after welding. Cleaning can be done by light pickling, by electropolishing, by light buffing, or by scouring with mild abrasives.

Cracks and voids in the weld nugget generally are a result of insufficient forging force or a hold time too brief to permit the weld metal to solidify under a given force. The high strength of stainless steel at elevated temperatures necessitates the use of high electrode force to make a sound weld. Flat-face, large-diameter electrodes provide a low unit pressure on the work-metal surface. An electrode having a small tip radius may produce a good weld, but can cause expulsion at the surface or at the interface of the two sheets, or excessive indentation. When the welding current is too high in relation to the electrode force, weld time and hold time, cracks can occur in the heat-affected zone as well as in the weld nugget.

Resistance Welding of Aluminum Alloys

*By the ASM Committee on Welding of Aluminum Alloys**

ALUMINUM ALLOYS, both the non-heat-treatable and heat treatable types, either wrought or cast, can be resistance welded, some more readily than others. Aluminum alloys have comparatively high thermal and electrical conductivity, a relatively narrow plastic range (about 200 to 400 F temperature differential between softening and melting), considerable shrinkage during cooling, a troublesome surface oxide, and an affinity for copper electrode materials.

Resistance spot and seam welding of aluminum alloys are used in the manufacture of cooking utensils, tanks (both for seams and for securing baffles), bridge flooring, and many aircraft components. Resistance welding of aluminum aircraft components such as wing-skin sections, deck sections, brackets and cowling usually involves making many high-quality welds in one structure, and may require elaborate and expensive equipment for cleaning, welding and control of weld quality. In many commercial applications, resistance welding of aluminum is done with less cleaning and a lower level of acceptable weld quality.

*For committee list, see page 296.

Weld Strength. The strength of resistance welds in aluminum alloys varies with the alloy and its thickness. Resistance welds should be located so that the weld is under shear loading. For tensile or combined loading, the tensile strength of the welded joint is only about 25% of the shear strength. Nuggets with diameters equal to two thicknesses of base metal plus 0.06 in. should have shear strengths greater than the values given in Table 1.

The heat of resistance welding decreases the strength and hardness of strain hardened and of solution treated and precipitation hardened aluminum alloys, depending on the temperature attained and the length of time that a temperature of 400 F or more is maintained during welding.

Base Metals

Although all aluminum alloys can be resistance spot and seam welded, some alloys or combinations of alloys have higher as-welded properties than others. Melting ranges, electrical and thermal conductivities, and resistance weldability of some wrought alloys and casting alloys are given in Table 2.

Resistance welding is also done on alclad products made by roll cladding some of the alloys listed in Table 2 with a thin layer of aluminum, or an aluminum alloy, that is anodic to the core alloy and thus provides electrochemical protection for exposed areas of the core. Alclad alloys 2219, 3003, 3004, 6061 and 7075 have a cladding of alloy 7072, which contains 1% zinc; alclad alloy 2014 has a cladding of alloy 6006, or sometimes of alloy 6053, both of which contain about 1.2% magnesium; and alclad alloy 2024 has a cladding of alloy 1230, which contains a minimum of 99.3% aluminum.

The hardness of an alloy affects its weldability. Any alloy in the annealed condition (O temper) is more difficult to weld than the same alloy in a harder temper. In general, alloys in the softer tempers are much more susceptible to excessive indentation and sheet separation, and to low or inconsistent weld strength. Greater deformation under the welding force causes an increase in the contact area and variations in the distribution of current and pressure. Therefore, welding of aluminum alloys in the annealed condition or in the softer tempers either requires

special electromechanical or electronic controls or else is not recommended.

High-strength alloys such as 2024 and 7075 are easy to resistance weld, but they may require special welding techniques because they are more susceptible to cracking and porosity than the lower-strength alloys. Sheet separation in welding high-strength alloys is low, and weld strength is consistent. Alloys clad with alloy 1230 or 7072 are less easily resistance welded than bare alloys of the same composition, because of the low electrical resistance and high melting point of the cladding at the contacting interfaces.

Although the strength of welds made in low-strength alloys such as 1100 and 3003 may vary, these alloys can be resistance welded readily in most applications. High welding current or low electrode force may be needed to compensate for the low electrical resistance of these alloys.

Shrinkage cracks in the weld metal are confined almost exclusively to welds made in the copper-bearing and zinc-bearing alloys such as 2024 and 7075. Such high-strength alloys, as well as the chromium-bearing alloys such as 5052 and 6053, may develop some porosity in the weld metal, particularly when they are welded in the hardened condition.

In joining dissimilar aluminum alloys, those with similar electrical conductivities and melting temperatures are easiest to weld together; those pairs with the greatest difference in electrical conductivity and melting temperature are the most difficult to weld together.

Wrought aluminum alloys are frequently spot welded to permanent mold, sand and die castings made from aluminum alloys. Of these types, permanent mold castings are easiest to weld, because the thickness is more nearly uniform. Such castings are sound, and have smooth surfaces and a low as-cast surface resistance, if welded within a reasonable time after casting. Die castings also are dimensionally accurate, but may require special cleaning to prepare the surface for welding, and sometimes special dies and foundry practice are needed to ensure the soundness of the metal in the region to be welded.

Spot and seam welds in non-heat-treatable alloys such as 1100, 3003 and 5052 are not selectively attacked by corrosion, but have the same corrosion resistance as the unwelded metal. Welds in heat treatable magnesium-silicon alloys such as 6061 and 6063 also have good corrosion resistance.

Welds in unclad *2xxx* and *7xxx* series alloys may be attacked preferentially under severely corrosive conditions and, therefore, weldments made from these alloys should not be used in a corrosive environment unless properly protected. However, when these same alloys are resistance welded to aluminum-clad parts of corresponding composition, the cladding electrochemically protects the unclad base metal at the interface and thus improves the over-all resistance to corrosion at the joint. Maximum resistance to corrosion at the welded joint is achieved when each of the parts being welded is an alclad alloy.

Factors Affecting Resistance Welding of Aluminum Alloys

Because of the inherent characteristics of aluminum alloys, resistance welding of these alloys requires procedures different from those used for resistance welding of steel. Included among these characteristics are high electrical and thermal conductivities, low melting-temperature ranges and low strengths at elevated temperatures, narrow plastic ranges, high shrinkage during solidification and the presence of natural oxide coatings.

Table 1. Minimum Shear Strength of Resistance Spot Welds in Aluminum Alloys

Thickness of thinnest sheet, in.	Minimum shear strength, lb per spot, for alloy: 1100-H14, 1100-H18	3003-H12, 3003-H18, 5052-O	5052-H32, 5052-H38, 6061-T4, 6061-T6, 5050-H34	2024-T3, alclad 2024-T3, 7075-T6, alclad 7075-T6
0.016	40	70	98	108
0.020	55	100	132	140
0.025	70	145	175	185
0.032	110	210	235	260
0.040	150	300	310	345
0.051	205	410	442	480
0.064	280	565	625	690
0.081	420	775	865	1050
0.102	520	950	1200	1535
0.125	590	1000	1625	2120

SOURCE: "Welding Alcoa Aluminum", Aluminum Co. of America, Pittsburgh, 1969

Table 2. Melting Ranges, Electrical and Thermal Conductivities, and Resistance Weldability of Common Aluminum Alloys (a)

Alloy and temper	Melting range, F	Electrical conductivity, % IACS (b)	Relative thermal conductivity, % (c)	Resistance weldability (d)
Non-Heat-Treatable Wrought Aluminum Alloys				
EC-H19	...1195-1215	62	60	ST
1060-H18	..1195-1215	61	57	ST
1100-H18	..1190-1215	57	55	RW
3003-H18	..1190-1210	40	39	RW
3004-H38	..1165-1205	42	42	RW
5005-H38	..1170-1205	52	51	RW
5050-H38	..1160-1205	50	49	RW
5052-H38	..1100-1200	35	35	RW
5083-H321	.1065-1180	29	30	RW
5086-H34	..1084-1184	31	32	RW
5154-H38	..1100-1190	32	32	RW
5454-H34	..1115-1195	34	34	RW
5456-H321	.1060-1180	29	30	RW
Heat Treatable Wrought Aluminum Alloys				
2014-T6	... 950-1180	40	39	ST
2024-T36	.. 935-1180	30	31	ST
2219-T37	..1010-1190	28	29	ST
6061-T6	...1100-1200	43	43	RW
6063-T6	...1140-1210	53	51	RW
6101-T6	...1140-1205	57	55	RW
7075-T6	... 890-1180	33	33	ST
Aluminum Casting Alloys				
13-F	1065-1080	31	32	LW
43-F	1065-1170	37	37	RW
A108-F	 970-1135	37	37	ST
138-F	 945-1110	25	26	LW
A214-F	1075-1180	34	34	ST
220-T4	 840-1120	21	22	NR
333-T6	 960-1085	29	30	ST
C355-T61	..1015-1150	39	38	ST
356-T6	1035-1135	39	38	ST
C612-F	1120-1190	40	39	LW

(a) In this table, wrought alloys are identified by Aluminum Association designations, and casting alloys by industry designations. For Aluminum Association designations of casting alloys, see Table 2 on page 297 in the article on Arc Welding of Aluminum Alloys.

(b) International Annealed Copper Standard, volume basis at 68 F. For comparison, copper alloy 102 (oxygen-free copper) is 101% and low-carbon (1010) steel about 14%.

(c) Based on copper alloy 102 as 100%, which has a thermal conductivity of 226 Btu/sq ft/ft/hr/°F at 68 F. Low-carbon steel has a thermal conductivity of about 13% on this relative scale. (d) RW, readily weldable; ST, weldable in most applications but may require special techniques for specific applications; LW, limited weldability and usually requires special techniques; NR, welding not recommended.

Electrical and Thermal Conductivities. Aluminum alloys are much higher in electrical conductivity than most metals that are commonly resistance welded. For example, the electrical conductivity of alloy 2024 (one of the low-conductivity aluminum alloys) is more than twice that of low-carbon steel. This high electrical conductivity necessitates the use of high-capacity welding machines capable of supplying high welding currents, because high current density is needed to generate enough heat to melt the aluminum alloy and produce the weld. The high thermal conductivity of aluminum alloys necessitates rapid welding to avoid dissipation of heat into the workpieces.

Effect of Melting Temperature. As the temperature is increased during resistance welding, aluminum alloys soften more rapidly and at lower temperatures than does steel. Low-inertia welding-machine heads are needed so that electrodes can make the rapid movements necessary for maintenance of weld force and workpiece contact. Although these movements are small, they must take place during an interval of about 2 to 5 milliseconds.

The plastic range in which a weld can be made is very narrow for aluminum alloys. Therefore, the energy input to the weld must be precisely controlled to bring the metal up to, but not above, its plastic range.

Effect of Shrinkage During Cooling. Aluminum alloys exhibit considerable shrinkage during cooling from the liquidus temperature to room temperature. This property is most pronounced in the high-strength heat treatable alloys such as 2024 and 7075, and can result in cracking. The non-heat-treatable alloys and the *6xxx* series alloys are less likely to crack as a result of shrinkage of the nugget.

Porosity and cracking can result from shrinkage unless the electrodes can maintain proper pressure on the nugget until solidification is completed. Machines for welding aluminum alloys generally have, in addition to low-inertia heads, a means of increasing the electrode force as the nugget solidifies. This permits forging of the nugget, and thus improves weld soundness.

Effect of Surface Oxide. Aluminum combines almost instantaneously with oxygen in the atmosphere to produce an aluminum oxide coating that has a high and somewhat erratic electrical resistance, which in turn affects the amount of heat produced in the metal beneath during resistance welding. Therefore, for aircraft-quality welds, this oxide film should be removed or changed to a film of uniform electrical resistance before welding.

Commercial spot or seam welding often can be done on aluminum without cleaning or oxide removal, but electrode pickup increases, electrode life decreases, and welds will be lower in shear strength, variable in quality and erratic in shape. The amount of sur-

face preparation needed depends on the strength and quality requirements of the welded product and on the alloy being welded.

Resistance Welding Machines

Aluminum alloys can be resistance welded with single-phase direct-energy, three-phase direct-energy, and stored-energy machines. Best results are obtained by using a machine that has the following features:

1 Ability to handle high welding currents for short weld times
2 Synchronous electronic controls for weld time and welding current
3 A low-inertia welding head for rapid follow-up of electrode force
4 Slope control (for single-phase welding machines)
5 A multiple-electrode-force system to permit proper forging of the weld nugget, and re-dressing of electrodes.

The three types of machines are discussed briefly in the following paragraphs. For additional information, see the article on Resistance Spot Welding, beginning on page 401 in this volume.

Single-Phase Machines. Single-phase direct-energy machines have high intermittent kva demand and low power factor, and may disturb other electrical equipment. A wide variation in line voltage can cause nonuniformity in welding. However, adequate transformers or substations reduce the variation.

The addition of upslope and downslope control to a single-phase machine is recommended for spot welding of aluminum (see discussion headed "Slope control", below).

Three-Phase Machines. Three-phase direct-energy machines, of either the frequency-converter or the dry-disk-rectifier types, produce excellent resistance welds in aluminum because of their partial control of the shape of the welding-current wave. The gradual increase in current at the beginning of the weld cycle and the decay at the end of the cycle are similar to the upslope and downslope used with single-phase machines.

Stored-Energy Machines. Electrostatic stored-energy machines use a three-phase full-wave rectifier to charge a capacitor bank to a predetermined voltage. The weld is made by discharging the bank of capacitors through a suitable welding transformer. The use of these machines has been largely superseded by three-phase direct-energy machines.

Synchronous controls for weld time and welding current are recommended for resistance welding of aluminum alloys because they provide precise control of short weld times and high welding currents. Magnetic and mechanical controls generally are not suitable.

Slope control permits adjustment of the rate of rise and fall of the welding current. Upslope control causes the welding current to increase gradually during the first few cycles of the weld time. The maximum current level is not reached until the electrode face has seated itself into the softened aluminum; therefore, excessively high currents do not normally occur at localized points. Overheating of metal at the interface of the electrode and the workpiece is reduced, which results in

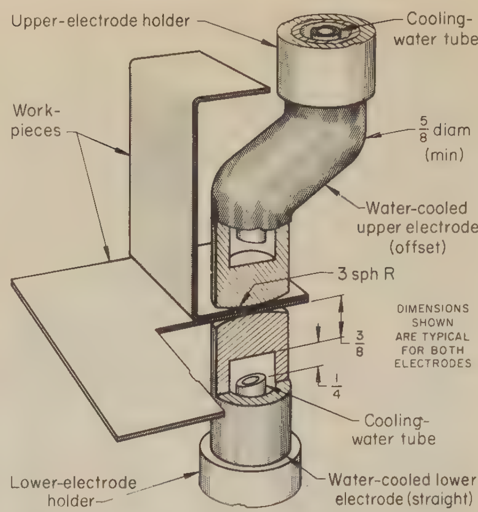


Fig. 1. Details of construction of straight and offset radius-face electrodes used in resistance spot welding of aluminum alloys

increased weld quality and electrode life and in better surface appearance.

Downslope control tapers the current off gradually, which prevents rapid chilling of the nugget. Downslope also permits better forging, which results in finer grain structure, eliminates cracks and voids in the nugget, and permits wider variations in amount and time of application of forging force.

Figure 16(b) on page 414 in the article on Resistance Spot Welding shows upslope and downslope in a weld cycle.

Multiple-electrode-force cycles usually consist of three stages. In the first stage, a high precompression force is exerted to seat the electrodes firmly on the work metal and to establish good electrical contact. The electrode force is then reduced to increase contact resistance while the weld is being made. After the nugget has formed, the force is again increased to forge the nugget. Figure 16(d) on page 414 in the article on Resistance Spot Welding shows a multiple-electrode-force cycle incorporated in the welding cycle.

A low electrode force for welding permits the use of a lower welding current and minimizes sheet separation. Use of high forging force reduces cracking. Multiple-electrode-force cycles make the accuracy of the machine settings less critical and increase the range in which high-quality welds can be produced.

Some welding machines can also produce an electrode force of 100 to 200 lb for use in re-dressing the electrodes with a paddle-type dresser.

Electrodes and Electrode Holders

Selection of electrode material and face shape, maintenance of the face and cooling of the electrode are important in producing consistent spot and seam welds in aluminum alloys.

Copper alloy electrodes, RWMA classes 1 and 2 (Table 2, page 409 in the article on Resistance Spot Welding), are used when welding aluminum alloys. These electrode materials have high electrical and thermal conductivities — which, together with adequate cooling, help to keep the temperature of the electrode below the relatively low point at which aluminum will alloy with copper, causing electrode pickup.

Design of Spot Welding Electrodes. Both straight and offset electrodes are suitable for spot welding of aluminum. However, straight electrodes should be used whenever possible, because deflection and skidding may occur with offset electrodes under similar welding conditions. If offset electrodes are used, the amount of offset should be the minimum permitted by the shape of the assembly being welded. Only electrodes that have the cooling-water hole within ⅜ in. of the face surface should be used. Fluted cooling-water holes provide more cooling surface than round holes. Construction details for both straight and offset electrodes suitable for spot welding of aluminum are shown in Fig. 1.

Face Contour. The face of at least one electrode must be shaped so that the current is highly concentrated at the weld. For most spot welding applications, an RWMA type F electrode, with a face having a spherical radius greater than the diameter of the electrode, is used on one or both sides of the workpieces. A radius face provides easy alignment and minimum sheet separation, concentrates the welding current, and is easier to clean and to maintain than is a flat face. One flat-face (RWMA type C) electrode can be used to minimize indentation on one workpiece, although higher joint strength usually is obtained by using equally radiused electrodes in joining workpieces of approximately equal thickness. (Types of electrode faces are described and shown in the section on Electrode Design, page 409, in the article on Resistance Spot Welding.)

Electrode-face radii for a variety of metal thicknesses and tempers are given in Table 3. When workpieces of dissimilar thickness are being welded, a radius-face electrode of correct dimensions should be used in contact with the thinner member; good-quality welds are more difficult to make if an electrode with too large a face radius or a flat-face electrode is used against the thinner workpiece.

Electrode Maintenance. Correct maintenance of electrode faces is essential if spot welds of uniform size and shape are to be made. The quality of resistance welds in aluminum alloys is more dependent on the contour, surface finish and cleanness of the electrode face than is the quality of welds made in other metals and alloys. The faces should be regularly re-dressed and periodically replaced or re-machined to their original shapes with properly designed tools when they show signs of wear or an appreciable change in contour. (Shaping of electrode faces by hand with a file is inaccurate and should be avoided.)

In the spot welding of aluminum alloys, electrode life is determined by metal pickup on the electrode face, and not deformation, as in the welding of steel. The copper-aluminum alloy formed on the electrode face by pickup is of low electrical conductivity and, if welding is continued, the electrodes will stick to the work metal and the surface of the work metal will melt. Aluminum must be removed from the

electrode face by periodic hand dressing to avoid marking the surfaces of succeeding welds and to maintain the original condition of the face.

Recommended practice is to clean the electrode when the center portion of the spot weld appears either dirty or crusty, or when work metal begins to adhere to the electrode. Less frequent cleaning will cause rapid electrode deterioration and poor weld quality. Electrode pickup can be minimized by proper preparation of the work-metal surface prior to welding, use of adequate electrode force, and avoidance of excessive welding current.

The cleaning operation must remove all the aluminum pickup, but must not change the face contour by removing an appreciable amount of electrode material. To maintain the original shape of radius-face electrodes, a dressing tool in the shape of a paddle with two depressions contoured to match the desired face radius should be used. The two depressions are faced with No. 240, or finer, abrasive cloth.

The dressing tool is clamped between the electrodes with a force of 100 to 200 lb and is rotated a few times to remove the copper-aluminum alloy. The faces are then cleaned, using a cloth dampened with a solvent, to remove any clinging abrasive dust, and then wiped dry. Abrasive grit or deep scratches in the electrode face caused by coarse grit can be transferred to the workpiece during welding, and thus should be avoided. A rubber block and two pieces of abrasive cloth can be used instead of a metal dressing tool.

Electrode Cooling. An adequate means of cooling the electrode face must be provided. This is usually done by a flow of water or refrigerated coolant through the inside of the electrode. Electrodes with either round or fluted water holes are available. Fluted holes provide more cooling surface than round holes. For continuous welding, each water-cooled electrode should be operated at a cooling-water flow rate of at least 1 gallon per minute, and preferably 1½ to 2 gallons per minute. The cooling water should be brought to within ¼ to ⅜ in. of the electrode face, and the inner cooling-water tube should extend to within ¼ in. of the bottom of the cooling-water hole to provide good circulation (see Fig. 1). The end of the cooling-water tube should be cut at an angle, so that if it bottoms in the cooling-water hole in the electrode, the water flow will not be stopped.

Cooling-water temperature should be 60 F or less, and should not vary more than 10 F. If the water temperature is above 60 F, or if it varies widely, the use of a refrigerated coolant may be helpful in improving electrode life and weld consistency. By cooling the electrodes with refrigerated coolant at temperatures of 38 to 40 F, the number of spot welds made between face cleanings can be increased appreciably. When a refrigerated coolant is used, however, condensation of water on the electrodes and electrode holders may present a problem.

Electrode Holders. The commercially available electrode holders are suitable for use in welding aluminum alloys.

Table 3. Face Radii for Resistance Spot Welding Electrodes or Seam Welding Electrode Wheels for Use on Aluminum Alloys of Various Thicknesses (a)

Condition of work metal	Radius, in., for work-metal thickness of: Up to 0.020 in.	0.021 to 0.032 in.	0.033 to 0.064 in.	0.065 to 0.094 in.	0.095 to 0.125 in.
Annealed or as-extruded	2	3	4	4	...
Intermediate tempers of non-heat-treatable alloys	2	3	3	4	6
Heat treated	1	2	3	4	6

(a) Spherical radii for faces of spot welding electrodes and transverse radii for edges of seam welding electrode wheels. When a flat surface is needed on one side of the workpiece, one electrode is made to the above radius, and the electrode that contacts the surface to be flat is either flat or has a 10-in.-radius face or edge. [Source of table: Same as Table 1]

Offset electrode holders sometimes are required for spot welding assemblies not accessible to straight holders and are preferred to offset electrodes because they are more rigid and less likely to cause skidding of electrodes.

Seam welding electrode wheels are from ⅜ to 1 in. thick and from 6 to 12 in. or more in diameter. An electrode wheel less than 6 in. in diameter sometimes is required, depending on the configuration or accessibility of the parts being welded. Electrode wheels usually have two curvatures — the radius of the wheel, which changes only slightly when the wheel is dressed, and the transverse radius of the crown on the edge of the wheel. Transverse radii of electrode wheels used for welding aluminum alloys of various thicknesses and tempers are given in Table 3. Electrode wheels with flat faces or with crowns 10 in. or more in radius can be used against work-metal surfaces to avoid marking or indentation.

Maintenance practices for seam welding electrodes are essentially the same as for spot welding electrodes. Electrode pickup can be removed from the face of an electrode wheel by dressing with a suitable grade of abrasive cloth. A moderately coarse grade of cloth produces a rough surface that prevents slippage between the wheel and the work metal. Some form of a medium-fine grade of abrasive held against the wheel under a load of 5 to 10 lb can be used for continuous dressing of electrode wheels. Knurl-driven electrode wheels should not be used because they roughen the surface of the wheel excessively, mark the aluminum work metal and cause electrode pickup.

Electrode wheels usually are cooled by a flow of water directed against the periphery of the wheel at the weld and sometimes are cooled internally.

Preweld Surface Preparation

Although welds satisfactory for some purposes can be made without any preweld surface preparation, welds free from cracks, porosity, and sheet separation and having maximum strength, symmetry, and consistency and that are economical are obtained only with correct procedures for cleaning and for reduction or removal of oxide film. Adequate surface preparation also reduces electrode contamination.

Commercial spot and seam welding of aluminum alloys such as 1100, 3003 and 5052 can be accomplished with only a degreasing and cleaning operation for surface preparation. However, consistency in commercial welding of the more highly alloyed compositions generally requires additional mechanical or chemical cleaning. Aircraft construction, regardless of the alloy used, demands the utmost in cleaning and oxide removal and requires continual checking of surface resistance.

Oxide can be removed by either mechanical or chemical methods. Usually, the length of time tolerable between oxide removal and welding varies from 48 hours to several days, depending on methods of oxide removal and handling and on storage environment.

Cleaning begins with the removal of any stencil identification marks with alcohol, paint thinner or other suitable solvent. Then parts heavily soiled with dirt, oil, grease, or lubricants from forming operations are cleaned with commercial solvents by wiping, dipping, washing, spraying, or vapor degreasing, depending on the size and quantity. Vapor degreasing with an acceptable chlorinated solvent generally is used whenever a large number of parts is involved. If only a few parts are to be cleaned, they can be immersed in or wiped with acceptable chlorinated solvents or acetone. Cleaning of metal with these chemicals should be done in a well ventilated area.

Degreasing is often followed by treatment with a nonetching alkaline cleaner specially formulated to produce low, consistent surface resistance on aluminum (see Alkaline Cleaning, page 615 in Volume 2 of this Handbook). After the cleaning operations, the work-metal surface should be able to support a water film without a break. Lightly soiled workpieces can be alkaline cleaned without degreasing.

Mechanical removal of oxides is primarily a hand operation and its effectiveness depends on the skill of the operator. The contact resistance of surfaces cleaned by this method sometimes is lower than that of surfaces cleaned by a chemical method. The cleaning action must be severe enough to cut through the hard oxide film, yet gentle enough not to form an excessively rough surface in the comparatively soft metal underneath.

When welding is confined to a small area and the oxide film is thin, mechanical methods provide quick and complete removal of the oxide film over that portion of the surface where the welds are to be made, with little investment for equipment, and without danger of subsequent formation of a high-resistance film. Mechanical cleaning can be done immediately preceding welding. Also, mechanical methods are useful for removing oxide from workpieces that are too large to be dipped and rinsed. After the workpieces have been degreased, the oxide film can be removed with a fine grade of abrasive cloth, a fine stainless steel wool or a motor-driven brush made of fine stain-

less steel wire. Glass brushes and aluminum wool have also been used. Carbon or low-alloy steel brushes or steel wool should not be used.

Chemical Removal of Oxides. An acid dip is used after heavy oxide removal or directly after cleaning, to obtain uniform surface resistance. A typical solution contains 12% (by volume) concentrated nitric acid, 0.4% (by volume) hydrofluoric acid and 0.2% (by weight) wetting agent, and is used at a temperature of 70 to 80 F. Immersion time in this solution is 2 to 6 min. This is followed by rinsing in clear water and drying.

Forgings, castings, extrusions or similar parts having thick oxide accumulation may need an alkaline etch before the acid dip. A commonly used alkaline-etch treatment is immersion in an aqueous solution of 5% sodium hydroxide at 150 to 160 F for 20 to 50 sec, followed by rinsing in cold water. The alkaline-etch solution may contain additives to prevent the formation of scale in the tank.

Aluminum alloys 1060, 1100 and 3003 and aluminum-clad alloys frequently are immersed for 1½ to 3 min in a warm (190 F) solution containing 10% (by volume) concentrated nitric acid, 6 oz sodium sulfate per gallon and 0.1% (by weight) wetting agent. The parts are then rinsed in cold running water for 5 min and dried rapidly. Heat treatable alloys such as 6061 are immersed for 1½ to 3 min in a warm (185 F) solution containing 15% (by volume) concentrated nitric acid, 13 oz sodium sulfate per gallon and 0.1% (by weight) wetting agent. The parts are then rinsed in cold running water for 5 min and dried rapidly. For more detailed information on cleaning and etching of aluminum alloys, see the article on Cleaning and Finishing of Aluminum and Aluminum Alloys, page 611 in Volume 2 of this Handbook.

To ensure satisfactory preparation of the surfaces for spot and seam welding, it must be determined that the cleaning and deoxidizing procedures are adequate and that the strength of the solutions is correct. This determination should be made by measuring the surface contact resistance after surface treatment of small coupons of the material to be welded; visual inspection is not a satisfactory control method. Measurement of contact resistance should be made also on each batch of workpieces being welded. Corrections in the procedures or additions to the solutions should be made as required to maintain the contact resistance of the control samples and of the workpieces at the desired value.

Occasionally, special surface-preparation methods are used to solve particular problems. For instance, in Example 293 in the article on Arc Welding of Aluminum Alloys, a method is described that met the exacting requirements of gas metal-arc and gas tungsten-arc welding on that job, and that could be adapted easily to preparation for resistance welding.

Contact-Resistance Test. A standard test can be used to determine the electrical resistance of an interface between aluminum alloy samples or workpieces. The two samples or workpieces are placed between two spot welding electrodes ⅝ in. in diameter with faces 3 in. in spherical radius, and are clamped under a static force of 600 lb. A 50-milliamp (ma) direct current is transmitted through the electrodes, and the resistance between the workpieces is determined with a suitable instrument.

The tests must be performed under identical conditions of force, applied current, and electrode size and contour. The measurement is sensitive to small changes in test procedure, and values are usually obtained by averaging at least 2 or 3 readings on each of the four possible interface combinations of a pair of specimens. Movement of either specimen after the electrode pressure is applied breaks the oxide coating and causes false low readings. The presence of burrs on the specimens also causes low readings.

The contact resistance of well cleaned aluminum alloys is from 10 to about 200 microhms, while that of unclean stock can be 1000 microhms or more. For noncritical welding, contact resistance of 200 to 500 microhms is satisfactory. For best results (as required for military applications), contact resistance should be about 50 microhms. A narrow spread in readings generally is preferable to low average values with an occasional high reading.

Seam Sealants. Elastic materials have been used between members of resistance welded joints to make containers fluid-tight and to limit interface corrosion, especially in high-hu-

Table 4. Typical Conditions for Resistance Spot Welding of Aluminum Alloy Sheets in 60-Cycle Single-Phase Direct-Energy Welding Machines

Thickness of thinnest sheet, in.	Electrode diameter, in.	Face radius, in. — Upper electrode	Face radius, in. — Lower electrode	Electrode force, lb	Weld time, cycles	Welding current, amp	Diameter of nugget, in.
0.016	⅝	1	Flat	320	4	15,000	0.110
0.020	⅝	1	Flat	340	5	18,000	0.125
0.025	⅝	2	Flat	390	6	21,800	0.140
0.032	⅝	2	Flat	500	6	26,000	0.160
0.040	⅝	3	Flat	600	8	30,700	0.180
0.051	⅝	3	Flat	660	8	33,000	0.210
0.064	⅝	3	Flat	750	10	35,900	0.250
0.072	⅝	4	4	800	10	38,000	0.275
0.081	⅞	4	4	860	10	41,800	0.300
0.091	⅞	6	6	950	12	46,000	0.330
0.102	⅞	6	6	1050	15	56,000	0.360
0.125	⅞	6	6	1300	15	76,000	0.425

Source: Same as Table 1

Table 5. Typical Conditions for Resistance Spot Welding of Aluminum Alloy Sheets in 60-Cycle Three-Phase Direct-Energy Welding Machines

Thickness of thinnest sheet, in.	Electrode diameter, in.	Electrode face radius, in.	Electrode force, lb — Weld	Electrode force, lb — Forge	Time, cycles — Weld	Time, cycles — Postheat	Current, amp — Weld	Current, amp — Postheat	Diameter of nugget, in.
Three-Phase Rectifier-Type Machines									
0.016	⅝	3	440	1000	1	None	19,000	None	0.110
0.020	⅝	3	520	1150	1	None	22,000	None	0.125
0.032	⅝	3	670	1540	2	None	28,000	None	0.160
0.040	⅝	3	730	1800	3	None	32,000	None	0.180
0.051	⅝	8	900	2250	4	4	37,000	30,000	0.210
0.064	⅝	8	1100	2900	5	5	43,000	36,000	0.250
0.072	⅝	8	1190	3240	6	7	48,000	38,000	0.275
0.081	⅞	8	1460	3800	7	9	52,000	42,000	0.300
0.091	⅞	8	1700	4300	8	11	56,000	45,000	0.330
0.102	⅞	8	1900	5000	9	14	61,000	49,000	0.360
0.125	⅞	8	2500	6500	10	22	69,000	54,000	0.425
Three-Phase Frequency-Converter-Type Machines									
0.020	⅝	3	500	None	½	None	26,000	None	0.125
0.025	⅝	3	500	1500	1	3	34,000	8,500	0.140
0.032	⅝	4	700	1800	1	4	36,000	9,000	0.160
0.040	⅝	4	800	2000	1	4	42,000	12,600	0.180
0.051	⅝	4	900	2300	1	5	46,000	13,800	0.210
0.064	⅝	6	1300	3000	2	5	54,000	18,900	0.250
0.072	⅝	6	1600	3600	2	6	61,000	21,350	0.275
0.081	⅞	6	2000	4300	3	6	65,000	22,750	0.300
0.091	⅞	6	2400	5300	3	8	75,000	30,000	0.330
0.102	⅞	8	2800	6800	3	8	85,000	34,000	0.360
0.125	⅞	8	4000	9000	4	10	100,000	45,000	0.425

Source: Same as Table 1

Table 6. Typical Conditions for Resistance Spot Welding of Aluminum Alloy Sheets in Capacitor-Type Stored-Energy Welding Machines

Thickness of thinnest sheet, in.	Electrode diameter, in.	Electrode face radius, in.	Electrode force, lb — Weld	Electrode force, lb — Forge	Condenser capacity, mfd	Condenser charge, volts	Transformer ratio	Total energy, watt-sec	Diameter of nugget, in.
0.020	⅝	3	376	692	240	2150	300:1	555	0.125
0.032	⅝	3	580	1300	240	2700	300:1	875	0.160
0.040	⅝	3	680	1580	360	2550	300:1	1172	0.180
0.051	⅝	3	890	2100	600	2560	300:1	1952	0.210
0.064	⅝	3	1080	2680	720	2700	300:1	2622	0.250
0.072	⅝	3	1230	3150	960	2750	450:1	3630	0.275
0.081	⅞	3	1550	4000	1440	2700	450:1	5250	0.300
0.091	⅞	3	1830	4660	1920	2650	450:1	6750	0.330
0.102	⅞	3	2025	5100	2520	2700	450:1	9180	0.360

Source: Same as Table 1

midity environments. For instance, welds of military quality can be made through gun-grade caulking compounds, which consist of finely divided aluminum powder in a special elastic binder, with no significant change in machine settings. Some tapes and paints provide equally good results.

Resistance Spot Welding

All of the commercial aluminum alloys that are produced as sheet, extrusions or castings can be spot welded; the combined maximum thickness with ordinary equipment is between ½ and ¾ in. Process control is much more critical than for spot welding of low-carbon steel, and the range of permissible welding-machine settings is narrower for a given work-metal thickness. Also, the condition of the work-metal surface is extremely important for production of satisfactory welds.

Figure 2 shows a typical spot weld between two 0.102-in.-thick sheets of alclad alloy 2024-T4 (alloy 1230 cladding; 99.3% min Al). In the center of this spot weld is an oval zone with an equiaxed grain structure. Surrounding this zone is a zone made up of a dendritic (or columnar) type of grain structure. The area of these two zones constitutes the spot weld nugget. Each is essentially a cast structure. The large size of the dendritic zone is the result of a welding technique that employed a postweld heat treatment permitting grain growth.

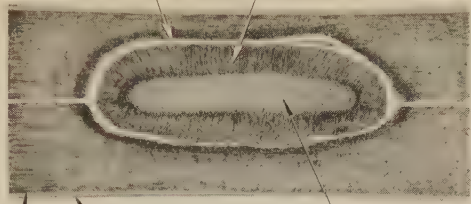
Surrounding the dendritic zone is a band of light color that consists of a layer of metal that has been heated close to the melting point, and in which segregation of eutectic material has occurred in the base metal. Forcing of this eutectic material into adjacent base metal results in a dark-color ring immediately surrounding the lighter ring. The cladding at the interface was completely absorbed with the base metal into the nugget. Indentation was not severe and the outer surfaces of the work metal in contact with the electrodes show no effect of heating.

Welding Current. As the thermal and electrical conductivities of aluminum alloys are about two to four times those of low-carbon steel, the heat for welding, and thus the welding current, must be greater than that used for welding steel of equivalent thickness. Tables 4, 5 and 6 list typical conditions for spot welding aluminum alloys in single-phase direct-energy, three-phase direct-energy, and capacitor-type stored-energy welding machines. These values are starting points and should be adjusted to suit the particular alloy and job requirements.

The higher the current, the more rapidly the nugget is formed. Also, the longer the duration of current flow, the greater the penetration of the nugget into the base metal. If the current is too low, the nugget forms too slowly, and excess heating and warping occur in the surrounding area. If the current is too high, formation of gas pockets and expulsion of metal result, causing sheet separation and weak welds.

Weld time is the actual time that the welding current flows through the workpieces, and must be sufficient to

Alclad alloy 2024-T4, 0.102 in. thick



Spot weld was made with a three-phase direct-energy resistance welding machine, using forging pressure and postheating. See text for discussion. (SOURCE: RWMA Bulletin 18)

Fig. 2. Typical spot weld nugget made in a heat treated alclad aluminum alloy

form the weld without excessively heating the remainder of the weld area. As work-metal thickness increases, longer weld times are required, as shown in Tables 4 and 5.

Within a narrow range of weld time, weld strength is approximately proportional to weld time. Using weld time beyond this range produces no appreciable further increase in weld strength.

Electrode force used for spot welding of aluminum alloys generally is greater than that needed for spot welding of steel of equivalent thickness. Low-strength aluminum alloys usually need lower electrode force than high-strength alloys.

Use of insufficient electrode force can result in expulsion of weld metal, internal defects, surface burning and excessive electrode pickup. Use of excessive electrode force can result in extreme indentation, sheet separation, work distortion, and asymmetrical welds. When a low electrode force is used, high contact resistance is developed at the interface, requiring a low welding current; when a high electrode force is used, contact resistance is reduced, and a higher current is needed.

A multiple-electrode-force cycle, in which the weld is made at a low electrode force followed by application of a higher force during hold time, is used to provide forging action during solidification of the nugget. In minimizing internal defects, timing of the application of forging force is important. If the forging force is applied before completion of weld time, the contact resistance is decreased excessively, and welds may be unsound. If forging force is applied too late, after the weld has solidified, forging will be ineffective.

Table 7. Suggested Minimum Joint Overlap, Weld Spacing and Distance Between Rows for Resistance Spot Welds in Aluminum Alloys

Thickness of thinnest sheet, in.	Minimum joint overlap, in.(a)	Minimum weld spacing, in.(b)	Minimum distance between rows, in.(c)
0.016	5/16	3/8	1/4
0.020	3/8	3/8	1/4
0.025	3/8	3/8	5/16
0.032	1/2	1/2	5/16
0.040	9/16	1/2	3/8
0.051	5/8	5/8	3/8
0.064	3/4	5/8	3/8
0.072	13/16	3/4	7/16
0.081	7/8	3/4	1/2
0.091	15/16	7/8	1/2
0.102	1	1	1/2
0.125	1 1/8	1 1/4	5/8

(a) Minimum edge distance is equal to one half of minimum overlap. (b) Measured from center to center. (c) For rows of staggered welds at minimum weld spacing. [Source of table: Same as Table 1]

Spacing of Spot Welds. When rows of spot welds are made, each successive weld can be affected by shunting of part of the welding current through the preceding welds. The shunting effect increases as spot spacing, work-metal thickness and electrical resistance of the alloy being welded decrease. Also, the shunting effect increases as the contact resistance between the workpieces increases.

In order to eliminate most of the shunting effect, the minimum spacing of spot welds made in aluminum alloy sheets normally should be no less than eight times the sheet thickness ($8t$), and preferably not less than the values given in Table 7. Where it is necessary to space welds at less than $8t$, the current can be increased after making the first spot weld to offset the loss from shunting. An alternative is to use two or more rows of spot welds with the welds in each row spaced apart by at least $8t$. Table 7 gives the suggested minimum distance between rows of staggered spot welds.

If a spot weld is made too close to the edge of a workpiece, the metal between the weld and the edge may bulge out or split, and molten metal may be expelled from the joint. The minimum distance a spot weld should be from the edge of a workpiece is one half the minimum joint overlap given in Table 7. If more than a single row of spot welds is made, the minimum overlap must be increased by the distance between rows.

Welding Practice. Use of the welding conditions given in Tables 4, 5 and 6 should produce welds having shear strengths exceeding those given in Table 1. Larger welds with proportionately higher shear strengths sometimes can be obtained with stored-energy equipment. Smaller welds with strengths lower than those given in Table 1 should be avoided. Settings that result in small-diameter welds in aluminum are likely to cause a substantial percentage of unacceptable welds under production conditions.

Although the welding conditions given in Tables 4, 5 and 6 are good starting points, optimum conditions must be determined by making and testing welds in sample setups of the job, and adjusting the given conditions accordingly. During production, it is necessary to test welds frequently to ensure that optimum conditions are maintained.

Welding conditions optimum for a specific application may vary substantially from those given in Tables 4, 5 and 6. For instance, in welding a 0.102-in.-thick handle flange to a 0.125-in.-thick frying pan (Fig. 3), both made of alloy 3003, using a three-phase frequency-converter welding machine, an electrode force of 1440 lb was used and a welding current of 70,000 amp was applied in two 5-cycle weld pulses separated by a 2-cycle off time for cooling the electrodes. With these conditions, output was 600 assemblies in 8 hours.

In welding workpieces of unequal thickness, the thinner workpiece governs

the welding conditions that should be used and the diameter of the resulting nugget.

Three or more thicknesses of aluminum alloy can be spot welded simultaneously. Conductivity of the alloy welded and thickness of the outside sheets govern the choice of machine settings. Because of the added resistance of the additional interfaces, electrode pressures are higher than those used for welding two sheets.

When spot welded aluminum assemblies must have smooth outer surfaces for purposes of aerodynamics or appearance, a flat-face electrode can be used on one side of the joint and a radius-face electrode on the other. Indentation will occur primarily on the side that contacts the contoured electrode, but some indentation results from shrinkage of the nugget. However, higher joint strength usually is achieved when electrodes of the same contour are applied to both sides of the joint, provided that the sheet thicknesses are about equal.

Preweld positioning of components by means of fixtures, clamps, spring fasteners or tack welds is recommended. Otherwise, some of the electrode force may be expended in bringing the components into contact, thus affecting the quality of the weld, especially if the effective electrode force varies. Mating parts should fit together so that the surfaces to be joined are in contact with each other, or can be readily pressed into contact with each other, at the weld area. All tooling that is in the throat of the machine during the welding operation should be nonmagnetic; aluminum, fiberglass and various types of plastics are often used.

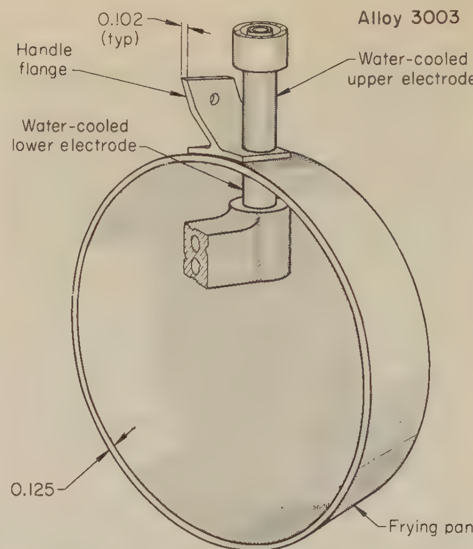


Fig. 3. Spot welding of a handle flange to an aluminum alloy frying pan

In the following example of spot welding for a military application, both fixturing and welding procedures were critical. In this example, as in spot welding of the frying pan shown in Fig. 3, the welding conditions finally selected differed substantially from those given in Tables 4 and 5.

Example 419. Resistance Spot Welding of Truck-Door Frames Using Both Press-Type and Portable Equipment (Fig. 4)

Structural frames for doors of military truck-tractors were made of alloy 6061-T6 extrusions and alloy 6061-T4 sheet, all 0.090 in. thick (see Fig. 4). The truck-tractors were designed to float in water through buoyancy of the all-aluminum cab, and the die-formed and unmachined mating surfaces between door and cab had to be accurately aligned to make watertight joints. Welding the heat treated and cold worked aluminum alloy gave rise to distortion difficulties, because the welding heat relieved high residual stresses. Welded construction was necessary, however, to meet the production demand of 400 frames per week.

A typical frame was held together by mechanical fasteners, as well as by welds at seven major joints. Five of the joints were resistance spot welded, by two different methods. The two other joints were gas metal-arc welded, as described in Example 303, in the article on Arc Welding of Aluminum Alloys.

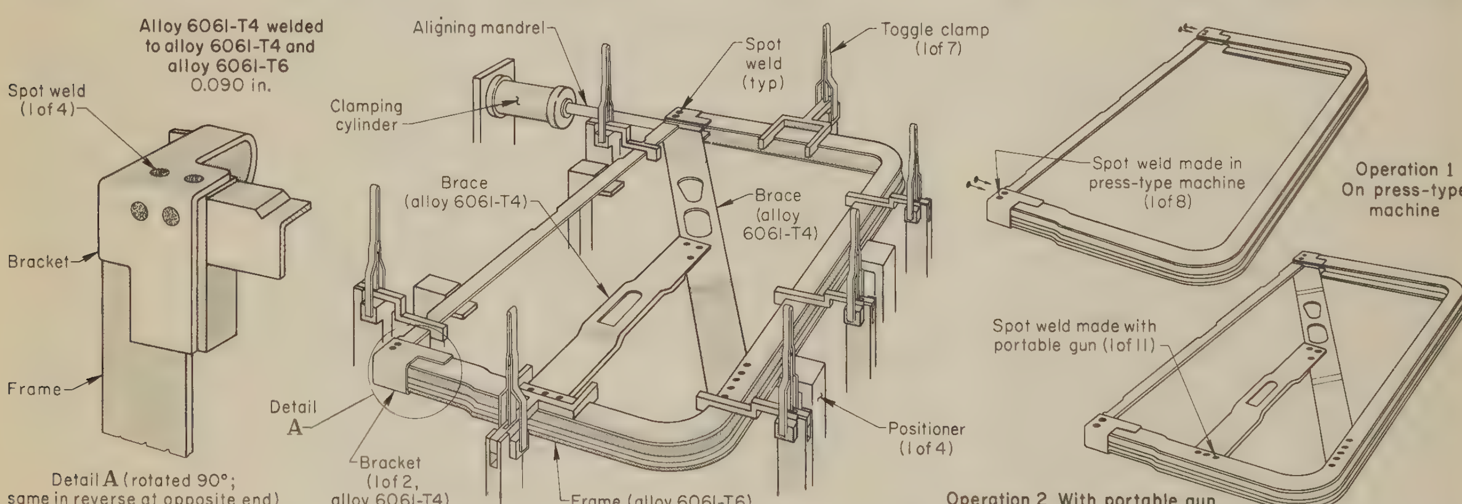
Cleaning for both methods of spot welding was the same; proprietary cleaners and oxide-removal solutions were applied to reduce the electrical resistance of joint surfaces to a range of 150 to 250 microhms. Prior to welding, the surfaces were wiped with oxide-removal solution.

Each of two corner brackets was attached to the extruded frame with four spot welds, as shown in detail A in Fig. 4. The brackets, aligned in a hand-held fixture, were welded in a press-type spot welding machine under the conditions given in the table with Fig. 4.

Then the subassembly was removed from the hand-held fixture and was placed in a floor fixture for the addition of two braces. A portable spot welding gun was used to weld a joint between the two braces and to weld two of four joints between the braces and the frame. The locations of the 11 spot welds at these joints are shown in the views at right in Fig. 4. Welding conditions for this operation are given in the table with Fig. 4.

Toggle clamps were used to hold the braces in alignment in the floor fixture, as shown in Fig. 4, and to prevent distortion of the formed outer-frame extrusion. A mandrel was inserted in one leg of the outer frame to serve as an alignment reference for the assembly.

Both the press-type welding machine and the portable gun had controls that enabled



Item	Welding of brackets	Welding of braces
Equipment Details		
Welding machine	Press type, 440 v, 60 cycle, 3-phase freq. converter(a)	Heavy-duty portable, 440 v, 60 cycle, single-phase(b)
Transformer	Series-parallel, no tap switch	Series-parallel, 4-step tap switch
Rating at 50% duty cycle	100 kva	250 kva
Welding controls	Synchronous, full and half cycle(c); phase-shift heat control	Nonsynchronous solid state, with slope control
Electrodes	RWMA class 1, 7/8-in. diam, type F face (4-in. radius)	RWMA class 1, 5/8-in. diam, type F face (4-in. radius)

Item	Welding of brackets	Welding of braces
Conditions for Resistance Spot Welding		
Welding current, amp	46,980	36,200
Transformer connection	Parallel	Parallel and No. 4 tap
Heat-control setting, %	87	90
Electrode force, lb	1200	1000
Squeeze time, cycles	20	12
Weld time, cycles	3	25
Hold time, cycles	25	12
Nugget diameter, in.	0.25	0.25
Weld spacing (approx), in.	1.5	1.5

(a) With 30-in. throat, air-operated low-inertia head, and electrode-dressing pressure. (b) With 6-in. throat, and electrode-dressing pressure. (c) Unipolarity and alternate polarity.

Fig. 4. Truck-door frame that was fabricated by resistance spot welding of brackets in a press-type machine, and by resistance spot welding of braces (using the fixturing shown) with a portable gun (Example 419)

the electrodes to be re-dressed in the machine, using a low-pressure contact on a paddle-type electrode dresser. The electrodes used in the press-type welding machine were dressed after making 80 to 100 welds, and those in the portable gun were dressed after 40 to 70 welds.

The order in which spot welds are made in a multiple-weld assembly is important in controlling warpage of the assembly and maintaining the strength of the spots. Making a spot weld produces slight lateral expansion of the work metal, and therefore spot welding preferably should be started from the center of the sheet and made in succession at the desired spacing toward the ends. Additional spot welds should not be made between two existing welds because shunting through adjacent spot welds could result in poor welds; also, expansion or warpage could prevent good contact of the sheets during welding. If three or more rows of welds are being made, the center row or rows should be made first.

Roll Resistance Spot Welding

Roll resistance spot welds can be made in conventional seam welding machines either with continuously rotating electrode wheels or with intermittent-motion electrode wheels. With intermittent motion, better surface appearance and better weld quality are obtained in welding aluminum alloys. Weld spacing is obtained by proper adjustment of electrode speed, or indexing time, and of the hold time. The individual roll resistance spot welds are essentially the same as resistance spot welds made in the conventional manner, except that shorter hold times are employed. With continuously rotating electrode wheels, heat times are usually shorter than those normally used for spot welding. The high current employed sometimes requires the use of high electrode force. Also, nuggets made by continuously rotating electrode wheels are usually elongated because of electrode travel.

Extruded or roll-formed sections frequently are roll spot welded to sheets. For instance, 0.060-in.-thick alloy 2024-T3 roll-formed Z-sections were attached to 0.060-in.-thick alloy 2024-T3 sheets to serve as stiffeners (see Fig. 5). The electrode wheels were stationary during welding (intermittent motion), and the electrode force was increased from 1500 lb for welding to 3600 lb for forging the nugget as it contracted during cooling, thereby producing high-quality, crack-free welds. The weld current of 55,000 amp was supplied from a 60-cycle three-phase frequency-converter welding machine in a single impulse of 2 cycles of heat time and 6 cycles of current decay. The 6-cycle current-decay time was an advantage because it served to decrease the cooling rate of the weld.

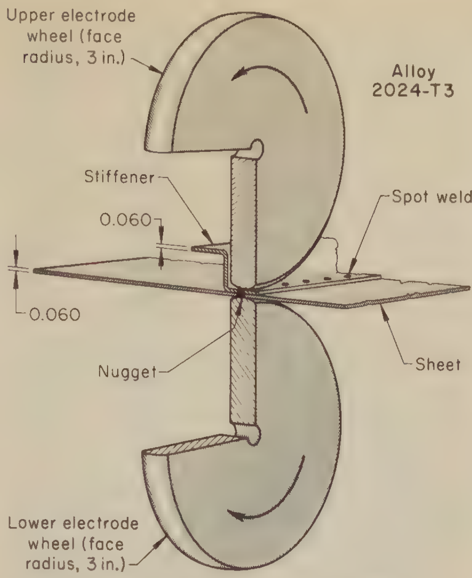


Fig. 5. Roll resistance spot welding of a Z-section longitudinal stiffener to a sheet, using intermittent electrode motion, a welding force and a forging force

Resistance Seam Welding

The overlapping spot welds produced in resistance seam welding result in a continuous gastight and liquid-tight seam. The welding current can be applied either when the wheels are moving or while they stop momentarily. Intermittent motion results in better surface appearance and better weld quality in aluminum alloys, and is ordinarily used for work of military quality when the work metal being seam welded is 0.080 in. or more in thickness.

Seam welding of aluminum alloys with continuously rotating electrodes was used in the assembly of the integral leading-edge wing fuel tank shown in Fig. 6. In this application, 0.040-in.-thick alloy 6061-T6 sheet was joined to 0.081-in.-thick alloy 2014-T6 clad sheet. Nylon rollers were used for guiding and supporting the workpieces and for easily moving the assembly between the electrode wheels without marring the work-metal surface. The welding force was 2800 lb. The weld current of 58,000 amp was supplied from a three-phase frequency-converter welding machine in a single impulse of 2 cycles preheat time and 4 cycles heat time, with 6 cycles cool time. The overlapping spot welds were made 12 to the inch at a rate of 25 in. per minute.

Typical conditions for seam welding alloy 5052-H34 using a conventional single-phase direct-energy seam welding machine are given in Table 8. Data in this table also can be used as a basis for developing conditions for welding other alloys or tempers. The maximum heat time should be between one fifth and one third the total time. Use of a heat time shorter than one fifth the total time helps to reduce electrode pickup, but also reduces nugget size. Electrode force, welding current, heat time, cool time and welding speed are adjusted to produce the desired spacing and weld width. Width of a seam weld should be twice the thickness of the sheet being welded plus 0.06 in. ($2t + 0.06$ in.).

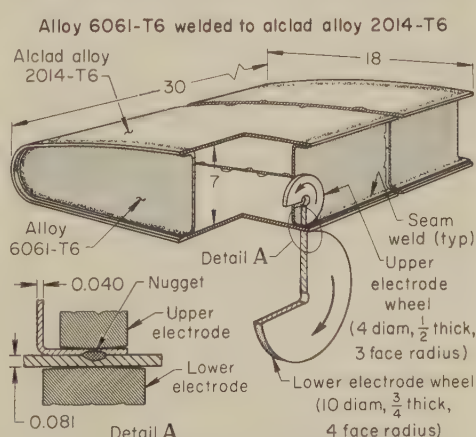


Fig. 6. Resistance seam welding of an aircraft integral wing fuel tank, using continuous electrode motion

Quality control for seam welding is the same as for spot welding except that an additional test, such as the pillow test, may be required for determining gastightness or liquid-tightness.

Projection Welding

Aluminum alloys are seldom projection welded, because extremely close control is needed in order to produce acceptable welds. Embossed projections like those used in low-carbon steel sheet, if made in aluminum alloy sheet, would collapse prematurely, and therefore are not used. Projections that have been coined in aluminum alloy workpieces are stronger and better able to resist collapse than are embossed projections, and are preferred.

Because of the narrow plastic range of aluminum alloys, the quality of projection welds is less uniform than that of spot welds of equivalent size.

Cross-Wire Welding

Aluminum alloy wires, round and in other shapes, can be cross-wire welded to make racks, grills or screens. Press-type resistance spot welding machines with low-inertia heads and fast follow-up are needed to maintain proper welding force on the joint as the wires deform and melt. Each cross-wire weld must be made individually; multiple-wire welding with bar electrodes has been unsatisfactory on aluminum alloys.

Selection of alloy and temper is the same as for spot welding. All aluminum alloy wires from about 1/16 to 3/8 in. in diameter can be cross-wire welded. Wires of equal diameters, or of unequal diameters in ratios up to 2 to 1, are readily weldable. Low-strength ring-type welds can result if the ratio of wire diameters is greater than 2 to 1.

Wire can be welded to a tube if the thickness of the tube wall is equal to or greater than the diameter of the wire. Wire can be welded to extruded aluminum alloy angles, or to other structural shapes, that have elongated projections extending at right angles to the wire direction. For optimum results, the cross-sectional radius of the projection should be approximately equal to the radius of the wire.

Optimum welding conditions are established by twist tests and by measuring setdown. Twist tests are made by twisting the wires so as to tear the area between wires. Tests of properly made cross-wire welds usually result in base-metal fracture outside the weld.

Setdown is the difference in the combined height of both wires before

Table 8. Typical Conditions for Making Gastight Resistance Seam Welds in Alloy 5052-H34 Sheets With 60-Cycle Single-Phase Direct-Energy Welding Machines(a)

Sheet thickness, in.	Spots per inch	Total weld time, cycles(b)	Wheel speed, fpm(c)	Heat time, cycles(d) Min	Max	Electrode force, lb(e)	Welding current, amp(e)	Width of weld, in.
0.010	25	3½	3.4	½	1	420	19,500	0.08
0.016	21	3½	4.1	½	1	500	22,000	0.09
0.020	20	4½	3.3	½	1½	540	24,000	0.10
0.025	18	5½	3.0	1	1½	600	26,000	0.11
0.032	16	5½	3.4	1	1½	690	29,000	0.13
0.040	14	7½	2.9	1½	2½	760	32,000	0.14
0.051	12	9½	2.6	1½	3	860	36,000	0.16
0.064	10	11½	2.6	2	3½	960	38,500	0.19
0.081	9	15½	2.1	3	5	1090	41,000	0.22
0.102	8	20½	1.8	4	6½	1230	43,000	0.26
0.125	7	28½	1.5	5½	9½	1350	45,000	0.32

(a) Electrode wheels and work metal must be cooled with 2 to 3 gallons of water per minute. (b) Heat time plus cool time. (c) Wheel speed is adjusted to give desired number of spots per inch. (d) Heat time must be set at full-cycle setting if total time is set at full-cycle setting. (e) Electrode force and welding current are adjusted to give desired width of weld. Values are for 5052-H34 aluminum alloy. Lower forces should be used for 5052-O and 3003-H14 aluminum alloys. [Source of table: Same as Table 1]

and after welding. For joints between wires of equal diameter, setdown should be 25 to 35% of the combined height before welding. For joints between wires of unequal diameter, setdown should be 25 to 35% of twice the diameter of the smaller wire. The quality of cross-wire welds is usually consistent when, during a production run, the variation in setdown does not exceed ±5% of the nominal value.

Flash Welding

All wrought aluminum alloys can be joined by flash welding. The process is particularly suitable for making butt and miter joints between two workpieces of similar cross-sectional shape. Aluminum alloy bars and tubes can be flash welded to copper bars and tubes.

Machines for flash welding of aluminum alloys require much larger transformer capacity than is needed for flash welding of steel. For best results, the welding machine must be capable of supplying a current density of 100,000 amp per sq in. while the workpieces are held in firm contact, without arcing. A secondary voltage of 2 to 20 v is required. Upsetting pressures are 8,000 to 40,000 psi.

Copper alloy clamping dies, RWMA classes 1 and 2, are used when flash welding aluminum alloys if a long die life is required. Hard-drawn copper may be used instead if a limited number of pieces are to be welded.

Initial die spacing varies according to work-metal thickness. About ½ in. of initial die spacing is suitable for thin-wall tubing and for thin sheets or extrusions, and about 1 in. is needed for flash welding a ¾-in.-diam bar.

Pinch-off dies provide the best weld quality in flash welding of aluminum alloys. These dies are made of hardened steel and are sharpened to a cutting edge. They are used to trim the upset metal or flash from the joint at the end of the upsetting stroke.

For additional information, see the article on Flash Welding, page 485 in this volume. Examples 432 and 434 in that article present applications of flash welding of aluminum alloys.

Inspection and Testing

Peel, twist or tear tests are common methods of determining the quality of resistance welds made in aluminum alloys. To meet commercial requirements, a button of metal having a diameter at least twice the thickness of the thinnest workpiece plus 0.06 in. ($2t + 0.06$ in.) should be pulled from one of the workpieces at each weld. To meet military standards, the button diameter should be equal to or exceed the nugget diameter given in Tables 4, 5 and 6. Spot welds in aluminum alloys 2014, 2024, 6061 and 7075, either bare or clad, will not always pull buttons completely through the sheet when the work-metal thickness is greater than about 0.080 in. In these alloys and metal thicknesses, the weld is peel tested and the diameter of the fractured area is determined.

When peel testing indicates that welds of the proper size are being produced, test welds can be made for use in determining shear strength. Welds also can be sectioned for metallographic examination to determine nugget diameter, penetration and microstructure. Radiographic examination can be used to determine the soundness of test welds.

During production, visual examination can be used to detect electrode pickup, surface burning, cracks, skidding, expulsion of molten metal, and excessive indentation. Radiographic inspection can, in some alloys, be used to detect internal defects such as cracks, porosity, and segregation, and to evaluate the size and shape of the nugget and the structure of the weld metal. In general, radiographic examination is used principally in the establishment of optimum welding conditions, and not as a production-control method. Other inspection methods sometimes used are eddy current, ultrasonic and sonic.

Indentation of the base metal can be determined by measuring the thickness of the weld with ball-tip micrometers, or by determining the difference in height between the weld and the surrounding area using a dial-indicator depth gage. Sheet separation can be measured with feeler gages.

Causes and Prevention of Weld Defects

Resistance weld defects most common in aluminum alloys include electrode pickup, cracks and porosity, expulsion of molten metal, indentation and sheet separation, and irregular-shape and unfused welds.

Electrode pickup, or alloying of the work metal with the electrode material, is usually the result of excessive heating at the interface between the electrode and the work metal. In severe cases, there is actual melting or burning of the work-metal surface.

Electrode pickup can be minimized by using adequate electrode force during welding, or by not using excessive welding current or weld time. Pickup may be caused by improper cleaning of work metal or electrodes, by use of improper electrode material, size, or contour, by inadequate cooling of the electrodes, or by skidding. Electrode pickup can occur with all types of welding equipment, but it usually occurs sooner when welding is done with the use of single-phase alternating-current equipment.

Cracks and porosity in the weld metal may result from too-rapid heating of the weld metal, an excessively high cooling rate, or inadequate or incorrect application of electrode force during or after welding. Spot welds in some high-strength alloys such as 2024 and 7075 are subject to cracking if welding current is too high or electrode force during welding is too low. Cracking may also result from too-rapid quenching of the weld metal after the welding current has been turned off. Changes in the downslope of the current or the use of postheating may eliminate cracking. On machines with dual electrode force, readjustment of the forge-starting time may also eliminate cracking.

Expulsion of molten metal from the weld area by flashing or arcing can usually be eliminated by use of better cleaning methods or by a slight reduction in welding current. Another cause of expulsion is an initial electrode force that is too low, followed by excessive forging pressure.

Indentation and sheet separation generally occur together. One of the major causes of these defects is the use of work metal of too soft a temper. These defects sometimes can be minimized by decreasing the electrode force, increasing the face radius of the electrode, or reducing the welding current or time. Sheet separation also can be caused by lack of flatness of the sheets being welded.

Welds with irregular shape and incomplete fusion are caused by incorrect fit-up of workpieces, incorrect electrode alignment, skidding of the electrodes, inadequate surface preparation, or an irregular electrode contour.

Inadequately fused welds in clad sheet may have some unfused cladding metal in the nugget. This defect can usually be avoided by a moderate increase in welding current.

Burning of holes through the workpieces can result from: (*a*) insufficient electrode force to squeeze the metal effectively; (*b*) the presence of foreign material such as paper or steel wool between the workpieces; (*c*) emery dust or emery cloth adhering to one or both electrodes; and (*d*) attempts to spot weld at points where there are screws, projections, or drilled holes. If none of these appear to be the cause of the difficulty, the welding machine and its controls should be inspected.

Resistance Welding of Copper and Copper Alloys

*By the ASM Committee on Welding and Brazing of Copper and Copper Alloys**

THE COPPERS AND COPPER ALLOYS that are most often resistance welded are listed in Table 1, which gives nominal compositions, melting points (liquidus temperatures), relative thermal and electrical conductivities, and welding indexes for resistance spot welding. Leaded and other free-machining copper alloys, which are seldom resistance welded, are not listed.

Spot welding is the resistance welding process most widely used for joining coppers and copper alloys. The principal applications are in welding sections up to about 0.060 in. thick, particularly on alloys that have low electrical conductivity. Many copper alloys with low conductivities can be seam welded easily. The coppers are difficult to seam weld. Projection welding is not recommended for copper or for most brasses. The bronzes can be projection welded with satisfactory results in many applications. Flash welding can be used for joining round stock, tubing, sheets and mill shapes made of copper and copper alloys. The abutting ends, as they become plastic, must be pushed together with a minimum of upsetting force to produce a satisfactory weld.

The articles on Resistance Spot Welding, Resistance Seam Welding, Projection Welding, and Flash Welding in this volume describe these processes.

Welding Characteristics

The resistance weldability of any copper or copper alloy is inversely proportional to its electrical and thermal conductivities. In general, the alloys with lower conductivities are easier to weld (see Table 1) and require lower welding currents (see Tables 1 and 2). Compared with steel, most copper alloys require shorter weld time, lower electrode force, higher current, and different electrode materials that are compatible with the alloy being welded. The conditions for spot welding various copper alloys are given in Table 2.

The minimum spot spacing and contacting overlap for spot welding high-zinc brasses are given in Table 3. When workpieces of unequal thickness are welded, spot spacing should be equal to the minimum spacing recommended for the average thickness. The values listed for contacting overlap are designed to prevent bulging of the edge and expulsion of weld metal in welding workpieces that are manually positioned between the electrodes. The contacting overlap can sometimes be less than shown when the workpieces are held in fixtures. Breaking loads in shear of spot welded joints are also listed in Table 3.

*For committee list, see page 337.

Welding Equipment

The moving-force member of a spot, seam or projection welding machine should be as light as possible to reduce inertia, and relatively free of friction to ensure rapid follow-up during welding. For a discussion of low-inertia heads and electrode holders, see page 437. Because copper alloys have a narrow plastic range, the force member must follow rapidly to maintain pressure on the joint and to prevent expulsion of weld metal.

Single-phase and three-phase direct-energy and electrostatic stored-energy (capacitor-discharge) welding machines are used for resistance welding of copper and copper alloys. The addition of slope control to single-phase direct-energy welding machines is not necessary for spot welding most copper alloys, although in welding high-zinc brasses, the use of upslope can result in an increase of as much as 20% in weld strength. Downslope is not recommended for welding any of the copper alloys. For a discussion of slope control, see the subsection beginning on page 468 in the article on Resistance Welding of Aluminum Alloys in this volume.

Electrostatic stored-energy machines use for the welding current an energy charge that is stored in a bank of capacitors. A three-phase, full-wave, grid-controlled thyratron rectifier is used for furnishing a direct-current power supply to the bank of capacitors. A vacuum-tube leveling circuit is used to predetermine and maintain the capacitor-voltage level.

During the instant of recharging the capacitors, the value of the rectifier current is determined by the impedance of the rectifier transformer and the resistance of a resistor in the circuit. The leveling circuit generally consists of an ordinary radio-tube-type circuit and the necessary direct-current positive-bias and negative-bias voltages for the proper on and off conduction time of the rectifier tube.

When the welding contactor is closed, the capacitor energy is discharged into a center-tapped welding transformer, and current flows into one half of the transformer. At the instant of closure, the rectifier tubes are automatically cut off by reversing the bias on the grid of the thyratron tubes to a high negative value. After discharge, the welding current ceases to flow, the rectifier tubes are made conductive by the reversal of the negative bias to a positive value, and the capacitors are automatically recharged. When successive welds are made, two welding contactors alternate the welding current between the two halves of the welding transformer to prevent saturation.

Generally, an electrostatic machine can be recharged rapidly enough to be used for roll-spot and seam welding as well as for spot and projection welding.

Welding-Machine Controls. Copper alloys are particularly sensitive to variations in welding conditions, and therefore all direct-energy machines used for welding these alloys should be equipped with synchronous electronic controls, especially in applications requiring short weld times. These devices are capable of controlling weld time and welding current for repeated operations with extreme accuracy, and of eliminating transient currents that sometimes result from random switching of power to the welding machine.

Electrodes

The current used for resistance welding of copper alloys is much higher than that used for welding low-carbon steel, and therefore the electrode must have high electrical conductivity to minimize heat buildup. Also, the thermal conductivity of the electrode must be high so that heat generated at the workpiece-electrode interface can be dissipated, preventing these surfaces from fusing. Proper cooling of the electrode is especially important for these alloys. Because of the low electrode force that is used in resistance welding of copper and copper alloys, deformation and wear of the electrode face have less effect on electrode life than does alloying of the face with the work metal.

Electrode Materials. The RWMA class 1 electrode materials, containing copper and cadmium, are sometimes used for welding copper and high-conductivity brass and bronze. Class 2 materials, containing copper and chromium, are used on low-conductivity brass and bronze and the copper-nickel alloys. Class 3 materials are used in electrodes for seam welding.

The RWMA group B materials (refractory metal compositions) are used as facings on electrodes for spot welding copper alloys because these materials do not readily alloy with copper alloys. Class 11 (a mixture of copper and tungsten), class 13 (commercially pure tungsten), and class 14 (commercially pure molybdenum) electrodes give good performance and long life when used in the resistance welding of copper and copper alloys that have high electrical conductivity.

Properties of electrode materials are listed in Tables 2 and 3, on page 409 in the article on Resistance Spot Welding in this volume.

Electrodes must be efficiently water cooled to minimize sticking to the work metal and to prolong their life. Face contours must be carefully prepared

Table 1. Nominal Compositions, Melting Points, Relative Thermal Conductivities, Relative Electrical Conductivities and Resistance Spot Welding Indexes for Some Coppers and Copper Alloys

Alloy No.	Alloy name	Nominal composition, %						Melting point, F (liquidus)	Relative thermal conductivity, % (a)	Relative electrical conductivity, % IACS (b)	Welding index (c)
		Cu	Zn	Pb	Sn	Ni	Other				
	OF and ETP Coppers										
102	Oxygen-free copper (OF) ...	99.95	...	...	...	...	...	1981	100	101	(g)
110	Electrolytic tough pitch copper (ETP)	99.90	...	...	...	...	0.04 O_2	1981	100	101	H-350
	Deoxidized Coppers										
120	Phosphorus-deoxidized copper, low residual phosphorus (DLP)	99.9	...	...	...	...	0.008 P	1981	99	97	...
122	Phosphorus-deoxidized copper, high residual phosphorus (DHP)	99.9	...	...	...	...	0.02 P	1981	87	85	(g)
	Beryllium Coppers										
175	High-conductivity beryllium copper, 0.6%	96.9	...	...	...	...	0.6 Be, 2.5 Co	1955	53-66(d)	45(d)	(h)
170	High-strength beryllium copper, 1.7%	98.3	...	...	...	...	1.7 Be	1800	27-33(d)	22(d)	C-150
172	High-strength beryllium copper, 1.9%	98.1	...	...	...	...	1.9 Be	1800	27-33(d)	22(d)	C-150
	Chromium Copper										
184	Chromium copper	99	...	...	...	...	1 Cr	1985	80(d)	78(d)	...
	Low-Zinc Brasses										
210	Gilding, 95%	95	5	...	...	...	...	1950	60	56	H-200
220	Commercial bronze, 90%	90	10	...	...	...	...	1910	48	44	H-200
230	Red brass, 85%	85	15	...	...	...	...	1880	41	37	H-200
240	Low brass, 80%	80	20	...	...	...	...	1830	36	32	G-175
	High-Zinc Brasses										
260	Cartridge brass, 70%	70	30	...	...	...	...	1750	31	28	E-150
268, 270	Yellow brass, 65%	65	35	...	...	...	...	1710	30	27	F-150
280	Muntz metal, 60%	60	40	...	...	...	...	1660	31	28	F-150
	Tin Brasses										
442 to 445	Admiralty	71	28	...	1	...	(e)	1720	28	25	(h)
464 to 467	Naval brass	60	39	...	0.75	...	(f)	1650	30	26	(h)
	Special Brasses										
667	Manganese brass	70	28	...	...	...	1.2 Mn	2000	25	17	...
675	Manganese bronze A	58.5	39	...	1	...	1.4 Fe, 0.1 Mn	1630	27	24	C-125
687	Aluminum brass, arsenical ..	77.5	20	...	...	...	2.2 Al, 0.06 As	1780	26	23	(h)
692	Silicon brass	90	8.5	...	...	...	1.2 Si	...	...	...	...
	Nickel Silvers										
745	Nickel silver 65-10	65	25	...	...	10	...	1870	12	9	C-125
752	Nickel silver 65-18	65	17	...	...	18	...	2030	8	6	C-125
754	Nickel silver 65-15	65	20	...	...	15	...	1970	9	7	C-125
757	Nickel silver 65-12	65	23	...	...	12	...	1900	10	8	(h)
770	Nickel silver 55-18	55	27	...	...	18	...	1930	8	5½	(h)
	Phosphor Bronzes										
505	Phosphor bronze, 1.25% E ..	98.7	...	...	1.3	...	0.2 P	1970	53	48	G-200
510	Phosphor bronze, 5% A	95	...	...	5	...	0.2 P	1920	18	15	D-125
521	Phosphor bronze, 8% C	92	...	...	8	...	0.2 P	1880	16	13	D-125
524	Phosphor bronze, 10% D	90	...	...	10	...	0.2 P	1830	13	11	D-125
	Aluminum Bronzes										
613	Aluminum bronze D, Sn-stabilized	89	...	...	0.35	...	7 Al, 3.5 Fe	1950	14	12	...
614	Aluminum bronze D	91	...	...	...	...	7 Al, 2 Fe, 1 Mn	1915	17	14	(h)
628	Aluminum bronze E	82	...	...	...	5	1 Mn, 2.5 Fe, 9.5 Al	1930	10	7.5	...
	Silicon Bronzes										
651	Low-silicon bronze B	98.5	...	...	...	...	1.5 Si	1940	15	12	B-125
655	High-silicon bronze A	97	...	...	...	...	3 Si	1880	9	7	B-125
	Copper Nickels										
706	Copper nickel, 10%	88.6	...	...	...	10	1.4 Fe, 1.0 Mn	2100	12	9	(h)
715	Copper nickel, 30%	70	...	...	...	30	...	2260	8	4.6	C-125
	Copper-Nickel-Manganese Alloy										
...	Copper-nickel-manganese age-hardenable alloy	60	...	...	...	20	20 Mn	1910	5	2.3-3.5	...

(a) Based on alloy 102, which has a thermal conductivity of 226 Btu/sq ft/ft/hr/°F at 68 F, as 100%. For comparison, 1010 steel has a thermal conductivity of 30 Btu/sq ft/ft/hr/°F, or about 13% on this relative scale. (b) The ratio of the resistivity of the International Annealed Copper Standard at 20 C to the resistivity of the material at 20 C, expressed in percent and calculated on a volume basis. (c) Welding index from the Third Edition of Volume I of the "Resistance Welding Manual", published by the Resistance Welder Manufacturers' Association. A is the basis of comparison, and is the equivalent of conditions for clean, cold rolled steel. B indicates that the alloy is readily weldable, but not as easily as steel. C, D, E, F and G represent progressive stages of increasing difficulty. G indicates that the alloy can be successfully welded, but 100% uniform results cannot be expected. H includes those metals which are considered commercially impractical to spot weld. The numbers following the letters indicate the approximate percentage of secondary current required, based on mild steel = 100. (d) In precipitation hardened condition. (e) Alloys 443, 444 and 445 contain a nominal 0.06% As, Sb or P, respectively. (f) Alloys 465, 466 and 467 contain a nominal 0.06% As, Sb or P, respectively. (g) Alloys not having a spot welding index by RWMA, but which are listed as not recommended for spot welding by the Copper Development Association. (h) Alloys not having a spot welding index by RWMA, but which are listed as good under suitability for being joined by spot welding by the Copper Development Association.

and the electrodes must be properly aligned for welding. Type F (radius-face) electrodes having a face radius of 3 to 6 in. are often used for spot welding copper alloys. The smaller face radii are used for welding thinner workpieces. A type C (flat-face) electrode is used where good appearance and minimum indentation are required on the surface of one workpiece. Rigid holders are needed to avoid deflection or skidding of the electrodes on the work when force is applied.

Selection of Process

Weldability of the work metal often determines which process should be used for a given application. Some of the coppers and copper alloys can be spot welded, but not seam welded because of high conductivity, and not projection welded because of low compressive strength of the projections at elevated temperature. (For further discussion, see the subsequent sections of specific alloys.) In welding dissimilar metals, heat balance can also be important in the choice of process.

Spot and seam welds can be made in work metal as thin as 0.001 in. Spot welding of metal as thick as 0.125 in. has been reported for copper alloys. Projection welding is best suited for work thicker than 0.020 in.

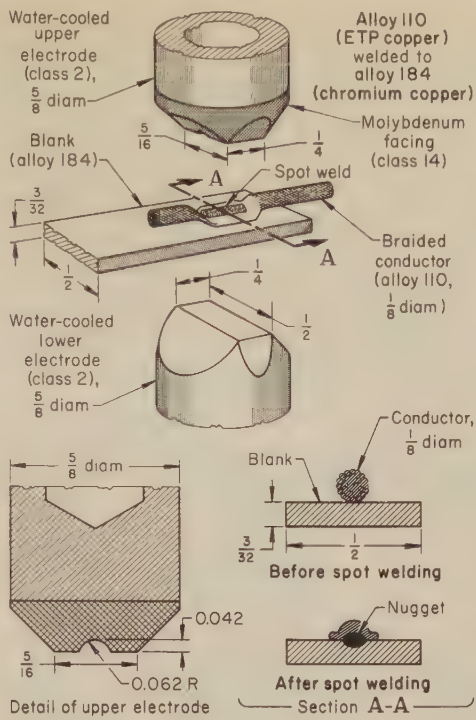
The use of projection welding frequently can increase the quality of joints in high-conductivity alloys, because welding current can be concentrated where needed. Distortion and electrode pickup are minimized because the electrode contacts a large area of the work metal. Projection welding may be preferred when the components are self-locating, or to simplify fixturing or improve dimensional accuracy.

Lap joints that must be liquid-tight usually are made most efficiently by seam welding. However, if a seam does not require the leaktightness provided by overlapping spots, spot welding is frequently preferred.

Electrode forces lower than those needed for welding low-carbon steel are used, but extremely low forces, which can cause electrode pickup, and weak welds, should be avoided. Low electrode force can also cause high-zinc alloys to flash or burn through.

Seam welding is nearly impossible on copper and many of the high-copper alloys, but most low-conductivity copper alloys can be seam welded readily using higher welding current and lower electrode force than those used for welding low-carbon steel. The usual spot spacing is 12 to 18 spots per inch. If fewer than 12 spots per inch are used, the spots sometimes do not overlap. Spots that are too closely spaced can cause excessive hot working of the base metal. Cooling by flooding, immersion or mist protects the work metal and electrodes from overheating and electrode pickup.

Projection welding is best suited for copper alloys of less than 30% electrical conductivity. The design of the projections in relation to the thickness and type of work metal is important. In general, to prevent collapse of the metal in the projection before welding temperature is reached, coined projections are preferred to formed projections. In Example 427, the projection was designed to minimize weld spatter and to contain the weld metal.



Conditions for Resistance Spot Welding

Lower electrode	⅝-in. diam, RWMA class 2, with ¼-by-½-in. face
Upper electrode	⅝-in. diam, RWMA class 2, ¼-by-5/16-in. class 14 face
Welding current	8500 amp, ac
Electrode force	350 lb
Squeeze time	10 cycles
Weld time	12 cycles
Hold time	16 cycles
Production rate	420 welds per hour

Fig. 1. Braided copper conductor and chromium copper blank that were joined by resistance spot welding, instead of by resistance brazing, to avoid use of a filler metal, minimize distortion of the blank and increase production (Example 420)

Preweld Cleaning

Dirt, scale, oil, drawing compound or other foreign matter on the surface of the workpiece should be removed before resistance welding. An indication of surface cleanness is the surface contact resistance, which should be uniform for best welding results. High or erratic contact resistance usually causes poor welds rather than reduced electrode life, although increased electrode pickup is an indication of high surface resistance. Surface cleaning can be done by various mechanical or chemical methods. See the article on Cleaning and Finishing of Copper and Copper Alloys, which starts on page 635 in Volume 2 of this Handbook.

Table 2. Conditions for Resistance Spot Welding Various Copper Alloys(a)

Alloy No.	Alloy name	Weld time, cycles	Electrode force, lb	Welding current, amp
230	Red brass	6	400	25,000
240	Low brass	6	400	24,000
260	Cartridge brass	4	400	25,000
268-270	Yellow brass	4	400	24,000
280	Muntz metal	4	400	21,000
510-524	Phosphor bronze	6	510	19,500
628	Aluminum bronze	4	510	21,000
651-655	Silicon bronze	6	400	16,500
667	Manganese brass	6	400	22,000
687	Aluminum brass	4	400	24,000
692	Silicon brass	6	510	22,000

Source: "Resistance Welding Manual", 3rd Ed., Vol 1, Resistance Welder Manufacturers' Assn, Philadelphia, 1956

(a) For spot welding 0.036-in.-thick sheet using RWMA type E electrodes with 3/16-in.-diam face and 30° chamfer, and made of RWMA class 1 material.

Coppers

Coppers and copper alloys having electrical conductivity higher than about 30% IACS (see Table 1) are the least suitable for resistance spot, projection or seam welding, mainly because of severe electrode pickup. Thin copper stock can be welded using electrodes faced with RWMA class 13 (tungsten) or class 14 (molybdenum), but surface appearance is poor and frequent electrode maintenance is required. A tinned coating on wire or sheet is helpful in welding copper.

When welding braided copper wires, best results are obtained if the wires are first bright dipped, then electrotin plated to a maximum thickness of 0.0002 in. Copper wires treated in this manner can be stored for 2 to 3 months, then welded with good results. The groove in the face of the electrode contacting the wire should have a depth not greater than one half the wire diameter. Tapering the electrode tip so that the length of the groove is equal to or slightly greater than the wire diameter will help prevent brittle welds. The sides of the electrode should be tapered in a like manner so that the face of the electrode is almost square in shape. The use of electrodes made of class 10 to 14 materials (refractory metals) helps heat the workpieces.

An internally water-cooled electrode with a molybdenum face shaped to conform to the top surface of the workpiece, and water cooling of the joint, were used in the example that follows. Clean joints were made at a higher production rate by spot welding than by resistance brazing.

Example 420. Joining a Braided Copper Conductor to a Chromium Copper Blank by Resistance Spot Welding vs Resistance Brazing (Fig. 1)

For joining a braided copper (alloy 110) conductor to an alloy 184 (chromium copper) blank, resistance spot welding was used instead of resistance brazing, to avoid

Table 3. Recommended Spot Spacing and Contacting Overlap, and Approximate Shear Load of Joint, for Resistance Spot Welding High-Zinc Brasses

Thickness of thinnest sheet, in.	Spot spacing, in., min	Contacting overlap, in., min(a)	Shear load of joint, lb
0.032	⅝	½	330
0.050	⅝	⅝	512
0.064	¾	¾	680
0.094	1	1	1168
0.125	1½	1¼	1872

Source: L. E. Mills and H. C. Wolfe, "Spot Welding 65-35 Brass On Single-Phase Equipment With Slope Control", RWMA Bulletin 25, Resistance Welder Manufacturers' Assn, Philadelphia

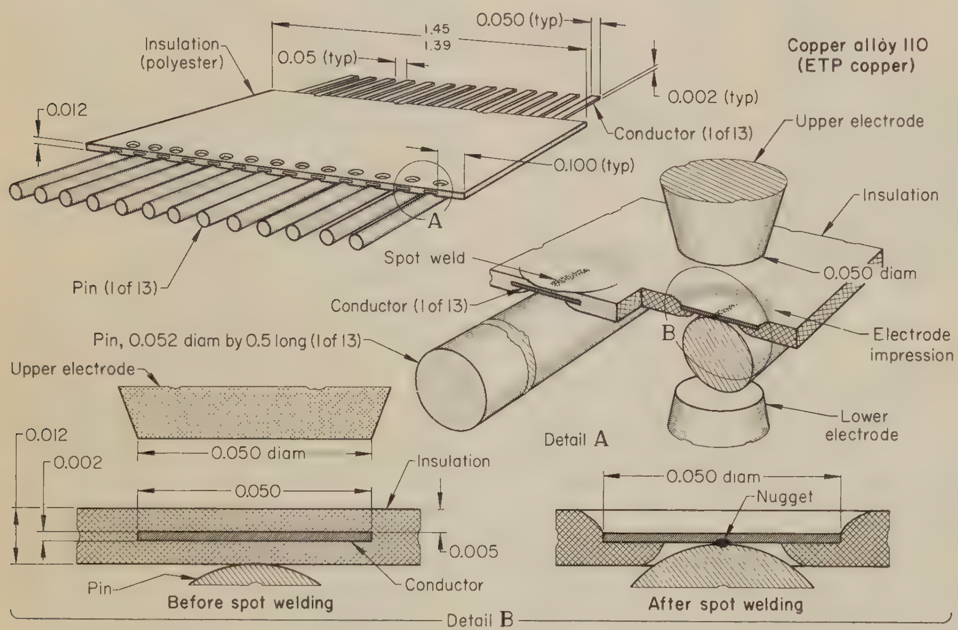
(a) Minimum edge distance is equal to one half the contacting overlap.

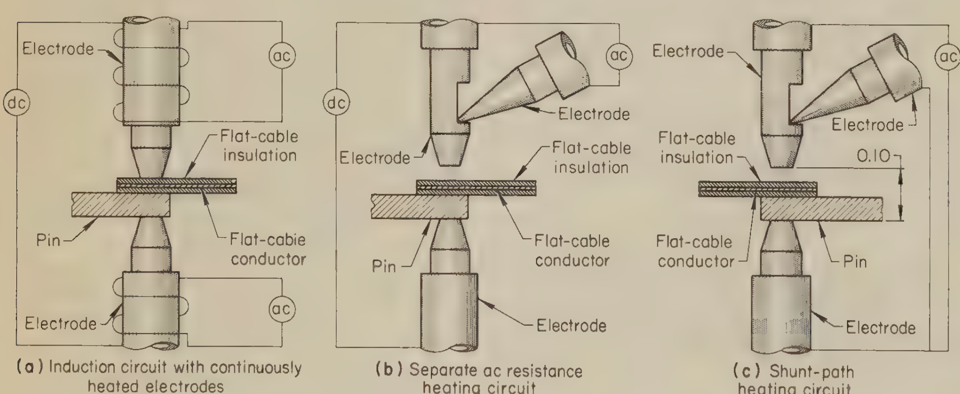
using a filler metal and to minimize annealing and distortion of the blank. Spot welding produced a joint of excellent conductivity and an assembly that was inherently clean because no flux or filler metal was used. The production rate for spot welding was more than twice that for resistance brazing, and thus a less costly part was produced by spot welding.

The ⅝-in.-diam water-cooled electrodes were made of RWMA class 2 material. The high conductivity of the copper conductor required that the upper electrode be faced with molybdenum (class 14 material) and be grooved, as shown in Fig. 1, to localize the contact area. The groove in the electrode face also helped to gather and hold together the strands of the conductor end as it was mashed to make a compact and dense weld. The lower electrode had a flat rectangular face ¼ by ½ in. As the weld was made, cooling water was directed on the joint to minimize annealing and to avoid burning of the copper conductor.

The production rate for spot welding was 420 welds per hour. Previously, when resistance brazing was used, production rate was 180 joints per hour. Resistance brazing required preplacement of a filler-metal disk, application of flux, use of a brazing time longer than the weld time used in spot welding, and excessive cleaning of the brazing electrodes.

Additional conditions for resistance spot welding are presented in the table that accompanies Fig. 1.





Equipment Details

Power supply	110-v single-phase ac(a), 220-v single-phase ac(b)
Welding machine	Press type, stored energy
Rating of capacitor bank	755 mfd
Storage voltage	13 to 408 v, dc
Energy storage	Low, 0.06 to 9 watt-sec; high, 0.1 to 45 watt-sec
Electrodes	1⁄16 in. in diam by 1¼ in. long, tapered to 0.05 in. in diam at tip, class 13
Electrode force	0.5 to 15 lb

Conditions for Resistance Spot Welding

Welding current	200 amp, dc
Welding voltage	0.6 v, dc
Electrode force	3 lb
Melting time	0.3 sec
Squeeze time	0.0025 sec
Weld time	0.0045 sec
Hold time	0.5 to 1 sec
Area of weld	40 sq mils (0.00004 sq in.)
Current density	5 amp per sq mil
Electrode gap	0.10 in.

(a) For heating the electrode to melt plastic insulation from the conductor. (b) For welding.

Electrode-heating circuits: (a) Induction circuit using alternating current for heating both upper and lower electrodes, and direct current for welding. When a high-temperature-resistant plastic insulation was used, electrode temperature offered considerable resistance to the flow of welding current. (b) Separate alternating-current circuit for heating the upper electrode only, and direct current for welding. (c) Alternating current for both heating and welding; shunt-path heating of upper electrode only.

Fig. 2. Three types of patented electrode-heating circuits, and setup for melting plastic insulation from copper conductors and resistance spot welding the conductors to copper pins, using a capacitor-discharge welding machine and the heating circuit shown at lower left (Example 421)

Often one or both members of a copper joint are coated with a protective or insulating material that interferes with direct welding of the joint. However, other considerations, such as expediency, loss of protection, or cost, may dictate that the coating not be stripped or cleaned away in a separate operation. Some coatings, like paint or insulation, can be penetrated by melting, burning or volatilizing them away during resistance welding. In Example 399, in the article on Projection Welding, a plastic sheet between two nickel wires was penetrated by pressure and heat that were applied to the rounded surfaces of the wires.

In the example that follows, a patented electrode-heating circuit was incorporated into the welding machine to burn or melt plastic coatings from copper conductors in welding the conductors to copper pins.

Example 421. Use of a Special Auxiliary Electrode-Heating Circuit To Melt Plastic Insulation From a Copper Conductor in Resistance Spot Welding (Fig. 2)

Plastic-coated conductors 0.050 in. wide by 0.002 in. thick were spot welded to 0.052-in.-diam pins using electrodes that were heated by an auxiliary alternating-current circuit to melt the 0.005-in.-thick insulation at the weld zone. Both components were made of copper alloy 110 (ETP copper). Thirteen conductors were contained in a flat connector board that was about 1⁷⁄₁₆ in. wide, as shown in Fig. 2. The insulation used on the parts described in this example was a polyester, but a higher-temperature-resistant plastic was sometimes used. Spot welding produced good joints at a high production rate without the need for stripping the insulation from the conductors.

Any of the patented heating circuits shown in Fig. 2(a, b or c) could be incorporated into a welding machine to melt through the plastic coating on the conductors. The system shown in Fig. 2(a) was selected for this application because it was superior to the other two with respect to all-around capabilities and performance. The direct-current welding circuit, because of its speed and dependability, was preferred for welding the copper workpieces. The electrodes were heated by heating elements powered by an alternating current. A disadvantage of this system is that when the electrodes were heated sufficiently to remove a high-temperature-resistant insulation, their resistance was increased and they would not easily pass direct current, and more electrical energy was required for welding. The welding cycle included a pulse of alternating current to melt the insulation, a squeeze time to bring the workpieces together and to allow the electrodes to cool, and a pulse of direct current to weld the workpieces together. Cooling the electrodes increased the efficiency of the direct-current welding pulse. Energy stored in a bank of capacitors was used for the welding current.

The circuit shown in Fig. 2(b) worked as well as the circuit shown in Fig. 2(a) and could be turned off between welds to cool the upper electrode, which was the only welding electrode in the heating circuit. The circuit shown in Fig. 2(c) used alternating current for both heating and welding. The alternating current could be used for welding the conductor to the pin if one of the components were made of a metal that was less conductive than copper.

Equipment details and welding conditions are given in the table with Fig. 2.

Resistance welding of small-diameter stranded copper wire to terminals made of either similar or dissimilar metal is difficult because the wires pro-

vide such a small heat sink that they melt before the mating workpiece reaches welding temperature. The copper-to-copper joint described in Example 655, in the article on Brazing of Copper Alloys, was made successfully by adding BCuP-5 filler metal and resistance brazing at a temperature below the melting point of the 0.014-in.-diam wires. Making the joint without a filler metal was unsuccessful because the small-diameter copper wires melted before a weld was made. In Example 420 in the present article, a braided copper conductor was successfully spot welded to a small chromium copper blank. In the example that follows, a stranded conductor containing 0.016-in.-diam wires was spot welded to a ring made of coin silver. The welding conditions were selected so that the maximum temperature reached in the two workpieces was above the melting point of the silver-copper eutectic (1436 F), but below the solidus temperature of ETP copper (1949 F).

Example 422. Careful Selection of Welding Conditions To Control Heating of Workpieces in Spot Welding (Fig. 3)

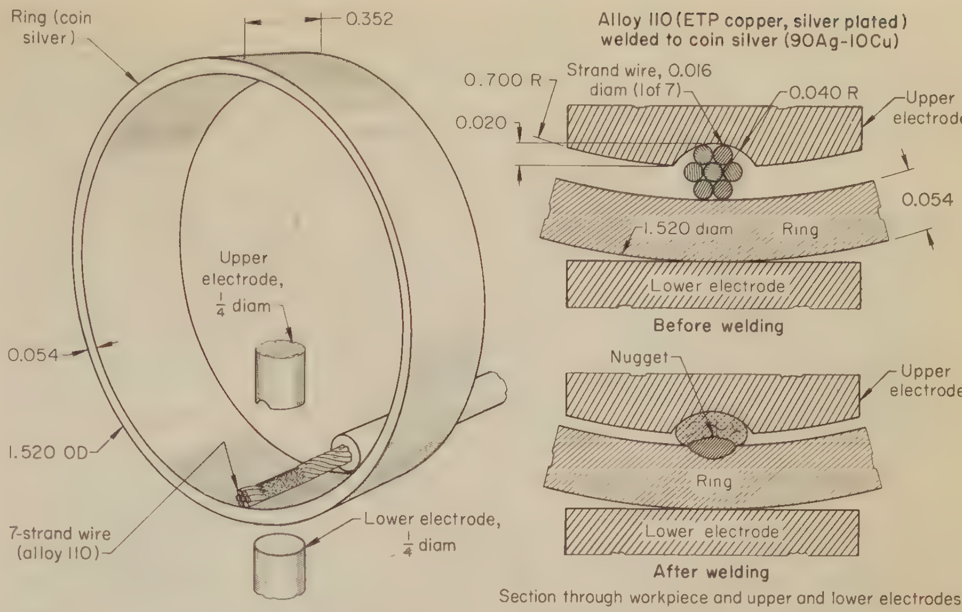
A silver-coated seven-strand lead wire of alloy 110 (ETP copper) was spot welded to a coin silver (90Ag-10Cu) ring at a production rate of 190 welds per hour. Originally, the assembly was made by lead-tin soldering, but the production rate was only 60 assemblies per hour and the solder spread over a large area of the ring. Also, brazing with silver alloy filler metal was not acceptable because of the increased cost and the need for removal of flux residue after brazing.

With the proper selection of electrode materials for resistance spot welding, shape of the electrode faces, and spot welding conditions, liquid started to form at the workpiece interface when the silver-copper eutectic temperature (1436 F) was reached, and the joint was fused without completely melting the small-diameter copper wires.

Use of a class 14 (molybdenum) electrode in contact with the copper wire and a class 2 (chromium copper) electrode in contact with the coin silver ring helped to maintain heat balance. The molybdenum electrode material promoted heating at the workpiece interface and prevented electrode pickup. A semicircular groove was machined into the upper (molybdenum) electrode to contain the stranded wire. The lower electrode had a flat face that made line contact with the ring and concentrated the welding heat. Both upper and lower electrodes were cooled by water flowing through passages in the electrode holders, and were cleaned by wire brushing after making 200 to 250 welds. Electrode life was about 5000 welds between redressings.

The coin silver ring was degreased with trichlorethylene before welding. Removing the insulation was the only preweld preparation needed for the wire. The ring was held in a vertical position against a stop; the wire was manually located beneath the upper electrode. The welding cycle was initiated with a pedal. Equipment details and welding conditions are given in the table with Fig. 3.

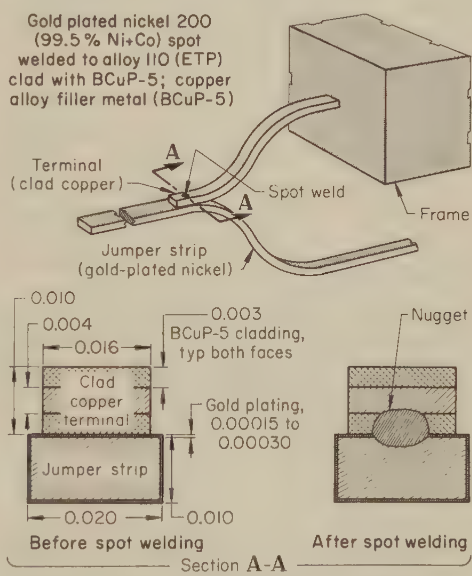
Spot welds can be made between metal-plated or metal-coated base metals, provided the thickness, composition and density of the coating are consistent. The ambient atmosphere and time between coating and welding can have an effect on the weldability of coated base metals. The contact resistance and the electrical resistivity of the coating can have a critical effect on spot welding of coated metals, as in the next example.



Equipment Details	
Power supply	440 v, three phase
Welding machine	Press-type
Rating at 50% duty cycle	100 kva
Lower electrode	Type C, ¼-in. diam, RWMA class 2
Upper electrode	¼-in. diam, RWMA class 14, with grooved face

Conditions for Resistance Spot Welding	
Welding current	70 amp, ac
Welding voltage	3.7 v
Heat-control setting	62%
Electrode force	120 lb
Squeeze and weld times	5 cycles each
Hold time	30 cycles
Production rate	190 welds per hour

Fig. 3. Stranded copper wire and coin silver ring that were resistance spot welded using electrode design and welding conditions given in the table to control heating of the workpieces (Example 422)



Equipment Details	
Welding machine	Press type, stored energy
Power supply	110 v, single-phase, 500 watts
Rating of capacitor bank	1500 mfd
Electrodes	RWMA class 2, 0.071-in. diam(a)

Conditions for Resistance Spot Welding	
Welding current	2500 amp
Electrode force	2.5 lb
Welding heat	20 watt-sec
Weld time	0.0012 sec
Hold time	1.0 sec

(a) Ends of electrodes were cut at 30° angle to provide elliptical faces; positive electrode was used in contact with the clad copper terminal.

Fig. 4. Gold-plated nickel jumper strip and clad copper terminal that were joined by resistance spot welding. Presence of more than 2% cobalt in the gold plating affected weld strength adversely. (Example 423)

Example 423. Effect of Composition of Plating on Quality of Spot Welds (Fig. 4)

A gold-plated nickel jumper strip was joined, as shown in Fig. 4, to a copper terminal clad with BCuP-5 (copper alloy brazing filler metal), by capacitor-discharge resistance spot welding. (The filler-metal coating was used for making other joints.) The spot welded joints were welded successfully for several years but, suddenly, joints made under the established welding conditions failed the specified 6.5-lb tensile-shear test. Adjustment of welding conditions did not produce acceptable welds.

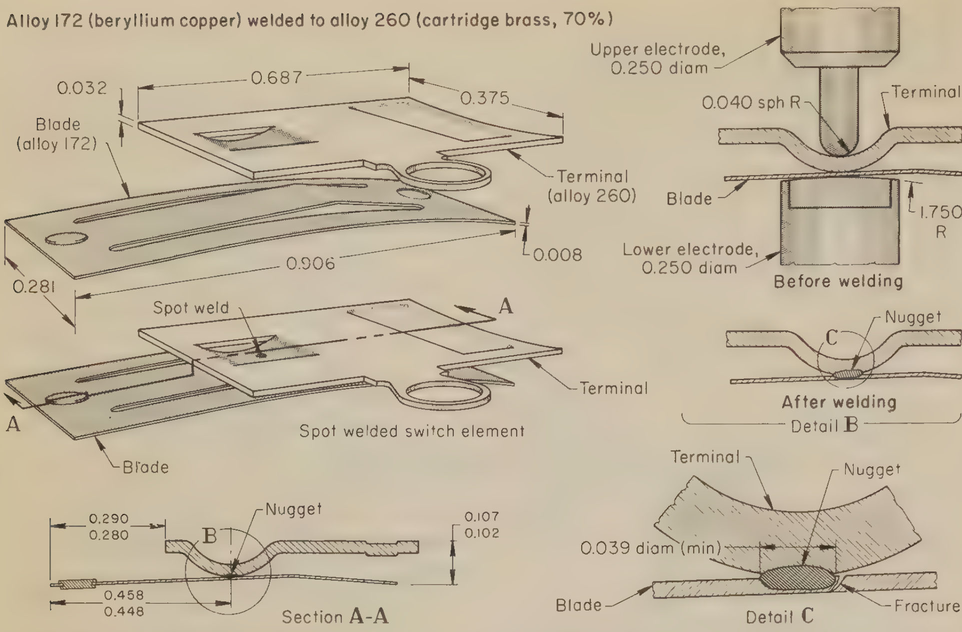
The 99.99% gold plating on the Nickel 200 (99.5% Ni+Co) jumper strip was 0.00015 to 0.00030 in. thick. The terminal was made of 0.004-in.-thick alloy 110 with an 0.003-in.-thick coating of BCuP-5 filler metal.

When tensile-shear breaking loads from 0.9 to 4.5 lb were obtained, instead of the specified 6.5-lb minimum value, it was found that the 99.99% gold plate had been changed to a hard gold plate containing a nominal 2% cobalt. Tests showed that 2% cobalt could be tolerated, but that the plating actually contained considerably more than 2% cobalt. When the plating was changed back to 99.99% gold, no further difficulty was encountered in maintaining the minimum 6.5-lb tensile-shear value.

Although the mechanism by which the cobalt weakened the joint was not known, variation in the thickness of the Au-2%Co plating caused a variation in contact resistance and a nonuniform electrical response to capacitor discharge. The IACS electrical conductivities of the metals in the joint were: copper, 101%; gold, 73.4%; nickel, 18%; and BCuP-5, 9.9%. Gold containing 1% cobalt has an electrical conductivity of 9.6%; a larger cobalt content decreases the conductivity of the plating more.

The weld nugget penetrated deeper into the nickel jumper strip than into the copper of the terminal, and there was no electrode identation on either side of the joint.

The electrodes were made of class 2 material and were 0.071 in. in diameter. The end of each electrode was cut at an angle



Equipment Details	
Power supply	110 v, single phase, 60 cycle, 20 amp
Welding machine	Press type, stored energy
Rating of capacitor bank	400 mfd
Storage voltage	100 to 1500 v, dc
Energy storage:	
Low	2 to 50 watt-sec
High	20 to 500 watt-sec
Output voltage	1.5 to 25 v
Electrodes	¼-in. diam, RWMA class 2
Upper-electrode face	0.040-in. spherical radius
Lower-electrode face	1.750-in.-radius crown, 0.125 in. wide

Conditions for Resistance Spot Welding	
Welding current	8000 amp
Welding voltage	12.5 v, dc
Welding energy	250 watt-sec
Electrode force	22 lb
Pulse time	2.5 millisec
Production rate	300 welds per hour

Fig. 5. Switch element that was made by capacitor-discharge resistance spot welding a beryllium copper blade to a cartridge brass terminal. Rejection rate was reduced by careful control of welding-machine setup and electrode maintenance. (Example 424)

of 30° to the centerline of the electrode, resulting in a face of elliptical shape with a major diameter of about ⁹⁄₆₄ in. The positive terminal of the welding machine was connected to the electrode that was in contact with the copper terminal. Additional equipment details and welding conditions are given in the table with Fig. 4.

The high-conductivity coppers have been projection welded to silver alloy contacts successfully. The copper workpieces were cleaned and plated with tin to a maximum thickness of 0.0002 in. The projections were coined on the silver contacts. Low electrode forces were used to prevent premature collapse of the projections during heating. An increased welding force and a fast electrode follow-up were used to ensure a good weld.

Tin plating kept the workpieces clean and the workpieces could be stored for 2 to 3 months without affecting weldability. There was a minimum amount of tin vaporization, and the tin melted and alloyed with the base metal with only a trace of flow during welding.

Nickel plating on copper can serve a similar function, and plating thickness and composition must be carefully controlled.

Beryllium Copper

Beryllium copper alloys can be resistance welded, most successfully in thin gages. Spot welding produces satisfactory welds; seam welding is less successful. Projection welding is satisfactory, provided that the projections can be formed with the work metal in the annealed condition and without cracking the work metal around the projection. Close control of welding conditions is required for consistent weld size and joint strength. Oxide films produced by heat treating must be removed to ensure low and consistent contact resistance. Work metals that have not been heated after rolling frequently need only degreasing before welding.

Low electrical conductivity (22% IACS for alloys 170 and 172) contributes to the weldability of beryllium copper alloys. However, they are more difficult to resistance weld than low-carbon steel. Alloy 175 has an electrical conductivity of 45% IACS, and is more difficult to resistance weld than higher-strength, lower-conductivity beryllium copper.

Resistance welding of beryllium copper requires the rapid heat input that can be provided by the short impulse length of a capacitor-discharge power supply. A low-inertia welding head is needed for fast follow-up to prevent expulsion of molten metal by arcing and to forge the weld nugget. Because capacitor discharge equipment supplies direct current, polarity can be a factor in weld strength when beryllium copper is welded to another copper alloy or to another metal.

In the two examples described next, beryllium copper was resistance welded either to itself or to a dissimilar metal. Capacitor-discharge welding was employed in two of the examples to produce high heat for a short time, which is needed to minimize diffusion of heat.

The size and location of the spot weld and the strength of the welded joint were important in obtaining maximum service life for the switch component described in the following example. Weld quality was maintained by setting up the welding machine carefully and by frequent electrode maintenance.

Example 424. Use of Careful Control of Welding-Machine Setup and Electrode Maintenance To Reduce Rejection Rate in Spot Welding (Fig. 5)

The snap-action switch element shown in Fig. 5 was produced by capacitor-discharge spot welding a blade made of alloy 172 (beryllium copper) to a terminal made of alloy 260 (cartridge brass, 70%). The location and size of the spot weld and the strength of the welded joint were critical in the performance and life of the switch.

If the weld joining the blade and terminal was too large, the blade failed prematurely by fatigue because of hardening in the heat-affected zone. As shown in Fig. 5 (detail C), the fracture developed in the heat-affected zone.

Mislocation of the weld either caused the blade not to have the snapping action, or changed other operating characteristics of the switch unacceptably. A riveted joint could not be used because the rivet hole in the blade so weakened it that the blade failed to have the snap action.

The rejection rate for the welded assemblies in snap-action testing sometimes was 25%, which could not be tolerated. Variations in the work-metal properties and in the welding equipment were at first suspected of causing poor switch life. Finally, the test failures were reduced to 5% by careful attention to the setup of the welding machine and to the shape and surface condition of the electrodes.

The electrodes were ¼ in. in diameter, and were made of class 2 material. The end of the upper electrode was reduced in diameter and had a 0.040-in. spherical radius; the lower electrode had a 1.750-in.-radius crown 0.125 in. wide.

During machine setup, the upper electrode was carefully clamped in its holder, and the upper electrode holder was lowered and temporarily locked so that a plate cam on the holder contacted the cam follower of a limit switch with the switch in the closed position. (This switch actuated the capacitor-discharge welding current.) The lower electrode was aligned, was raised until it touched the upper electrode, and then was clamped in its holder. The spring that provided the electrode force was then compressed so that it would exert a force of 22 lb on the workpieces during welding.

The components were held in a fixture during welding. The blade nest was adjusted to give the blade firm contact with the lower electrode, and the terminal nest was similarly adjusted for proper contact of terminal and blade so that the blade could not flex when force was exerted on the terminal by the upper electrode.

The electrodes were cleaned with crocus cloth after welding every 25 assemblies. When pitting developed on the lower electrode surface, the electrode was removed for refinishing. Refinishing of electrodes usually was a successful remedy when poor welds were produced.

The welded assemblies were subject to 100% inspection for snap action. The weld nugget was to be a minimum of 0.025 in. from the edge of the center leg, and molten metal formed during welding was to be confined between the blade and the protrusion on the terminal. If molten metal was ejected from this area, malfunction of the switch was possible. After welding, the blade surface had to be smooth and free of pitting; pitting would reduce service life. Also, the weld nugget was required to be strong enough to withstand 0.23 lb-in. of torque without permanent set in a torsion-shear test.

Destructive tests, in which a blade was peeled from the terminal, were made on

0.5% of the welded switch assemblies. To pass inspection, the blade had to pull a button 0.0012 sq in. in area (0.039 in. in diameter), or greater, yet small enough to fit completely under the end of a 0.062-in.-diam rod.

In the example of projection welding that follows, one of the workpieces was a nickel wire, and thus, as in cross-wire welding, a manufactured embossment was not needed for the projection. A capacitor-discharge power supply was used and, until the system was changed, the rate of recharging the capacitor bank affected the production rate, or the weld quality, if welding current was initiated before the capacitors were recharged. Polarity also had an effect on weld quality.

Example 425. Change in Power-Supply-and-Control System That Reduced the Number of Faulty Welds in Projection Welding (Fig. 6)

The gate module shown in Fig. 6 was used in a telephone thin-film circuit pack, and consisted, in part, of an electronic circuit deposited on a small glass substrate with 11 beryllium copper (alloy 172) clips 0.005 in. thick that served as electrical leads. The beryllium copper clips were joined to 0.023-in.-diam flash gold-plated nickel wires that were in a phenolic molded body. The completed module was subsequently installed on a printed circuit board. A stored-energy (capacitor-discharge) welding machine was used for the operation.

The beryllium copper clips were formed and mechanically attached to the glass substrate and soldered to the thin-film circuit, so that each clip was aligned and held in position during the clip-to-wire welding operation. The substrate and phenolic subassemblies were positioned by hand with the nickel wires and the beryllium copper clips overlapping for welding as shown in Fig. 6. The wire and clip were then manually positioned between the welding electrodes to make each of the 11 welds needed to complete the assembly.

The beryllium copper used for the clips was coated with 60-40 Pb-Sn solder to a thickness of 0.0002 in. The weld nugget undoubtedly contained some solder from the coating on the beryllium copper clip and some gold from the plating on the nickel wire. However, it would have been difficult to isolate the actual nugget metal because of the solder fillet that surrounded the nugget and joint. If the solder coating was too thick, welding heat was inadequate, but with the coating thicknesses used, the solder and gold did not affect the strength or ductility of the joint. Welding response was determined largely by the thermal conductivity of the beryllium copper, which required that the welding-current pulse be delivered quickly to minimize diffusion of heat.

The short pulse length of the capacitor-discharge welding current necessitated the use of a welding head with a low-inertia, fast-follow-up force system. The system used consisted of a decoupling spring between the ram and the electrode. Deflection of the spring actuated the welding switch on the downstroke when the correct welding force was reached. Because a capacitor-discharge pulse is direct current, weld properties are affected by the polarity of the electrodes during welding. The breaking load of the clip-to-wire welded joint was 13 lb or greater when the negative electrode was used against the nickel wire and the positive electrode against the beryllium copper clip, and only 4 lb when the electrodes were reversed.

Originally, the capacitor bank was discharged through a relay, and thus the welding current could be initiated before the capacitors were completely recharged. The pedal-release and relay-reset time was only 0.15 to 0.20 sec, while the capacitor-recharge time was 1.0 sec, so even an experienced operator, when making closely spaced welds or welds in closely spaced components, could initiate the welding current before the capacitor bank was sufficiently recharged. This led to faulty welds and it was necessary to change the system of supplying and controlling the power.

The system that was finally used was fully electronic with a capacitor-recharge time of 0.30 sec. Recharge was started automatically after a 0.15-sec shutoff pulse, even with the pedal depressed. In addition, a lockout circuit prevented the welding current from being initiated before the capacitors were 90% recharged. This feature reduced the number of faulty welds.

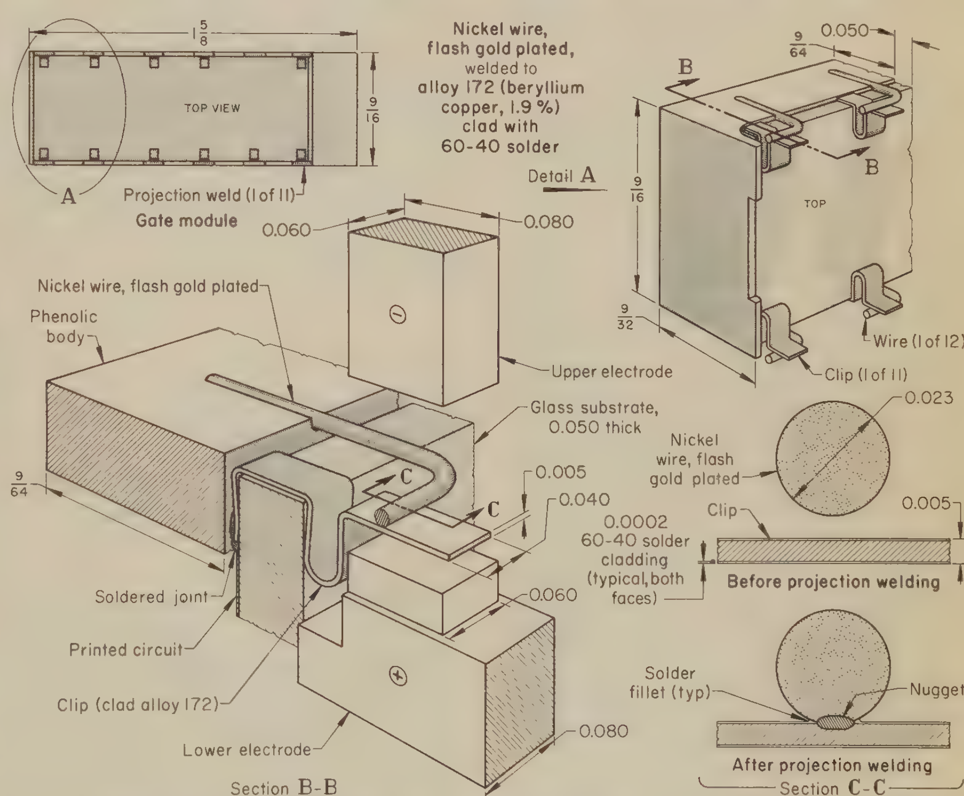
Electrodes of special shape helped to position the workpieces during welding and to control weld quality. The lower electrode positioned the glass substrate horizontally and supported the beryllium copper clip. Solder pickup was removed from the electrode faces by placing a fine emery cloth between the electrodes and reciprocating and oscillating the cloth while the electrodes were lightly closed.

The welding-machine settings were established experimentally by making and testing samples, then adjusting the machine settings until the samples met the minimum strength requirements. The test consisted of holding the wire of a simulated clip-to-wire weldment and pulling the tab at right angles to the wire. A minimum breaking load of 5 lb was required in this test. An average value of about 13 lb was observed on welds made with the correct polarity. Pull tests were made approximately every 4 hr. In addition, 10 welds per hour were tested by probing with a force gage that was calibrated at 200 grams to verify that there had been no change in the welding conditions that could result in weak welds. Weak welds found by probing were usually repairable by rewelding.

A beryllium copper blade that was welded to a steel support by projection welding had inadequate service life because of fatigue failure of the beryllium copper blade in the heat-affected zone. A successful redesign in which the beryllium copper blade was sandwiched between two steel supports is described in the following example.

Example 426. Projection Welding of Two Steel Supports To Hold a Beryllium Copper Blade That Was Sandwiched Between Them (Fig. 7)

The oscillating-contact assembly shown in Fig. 7 was made by sandwiching a beryllium copper alloy 172 blade between two supports made of cadmium-plated cold rolled low-carbon steel strip (ASTM A109), and then projection welding the supports together through holes in the beryllium copper blade so that the welds mechanically held the blade. The steel supports were 0.036 in. thick, and the beryllium copper blade was 0.010 in. thick.



Equipment Details

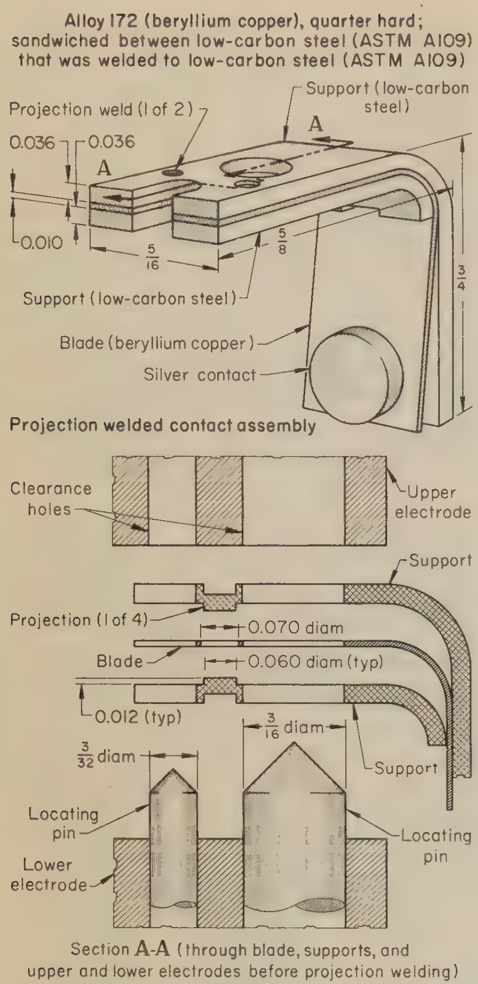
Power supply	120 v, single phase, 60 cycle, 6 amp (max)
Welding machine	Bench type, stored energy, with foot-operated low-inertia head
Rating of capacitor bank	14, 28 or 56 mfd
Storage voltage	675 to 1500 v, dc
Secondary current, max	3000 amp
Energy storage	0-63, 0-32 or 0-16 watt-sec
Pulse width	0.0018 to 0.0166 sec
Electrodes	RWMA class 2(a)
Electrode force, max	15 lb

Conditions for Resistance Spot Welding

Welding current	1900 amp
Welding voltage	2.8 v, dc
Weld energy	27 watt-sec
Electrode force	10 lb
Pulse time	0.005 sec
Production rate	1500 welds per hour

(a) Upper electrode was 3/16 in. in diameter by 1½ in. long, with a 0.060-by-0.080-in. face; lower electrode was a bar 0.080 by 3/8 by 1⅜ in. long, with a 0.060-by-0.080-in. contact surface. Weld strength was significantly greater when the positive electrode was used in contact with the beryllium copper clip.

Fig. 6. Gate module that was assembled by capacitor-discharge resistance projection welding nickel wires to beryllium copper clips in the setup shown. Change in system of supplying and controlling power reduced the number of faulty welds. (Example 425)



Equipment Details

Power supply	480 v, single-phase, 60 cycle
Welding machine	Press type with air and magnetic-actuated electrode force
Rating at 50% duty cycle	75 kva
Welding current, max	30,000 amp
Electrodes	5/8-in.-diam type C, RWMA class 1
Electrode force, max	Air actuated, 600 lb; magnetic actuated, not recorded
Welding controls	Synchronous, with phase-shift heat control
Fixturing	Pins fitted into lower electrode

Conditions for Projection Welding

Welding current	8500 amp, ac
Electrode force	Air actuated, 350 lb; magnetic actuated, not recorded
Squeeze time	30 cycles
Weld time	5 cycles
Hold time	5 cycles
Production rate	360 assemblies per hour

Fig. 7. Oscillating-contact assembly, made by projection welding two low-carbon steel supports through holes in a beryllium copper blade that was sandwiched between the supports (Example 426)

Formerly, the blade itself was projection welded to a single steel support by use of projections in the support. The weld was well formed, but the blade had a life of only 4 to 5 million cycles, compared with the required life of 10 to 15 million cycles. Failure was caused by cracks that originated in the heat-affected zone of the blade.

In the improved design, two projections in one steel support contacted two opposing matched projections in the other support through mating holes in the beryllium copper blade. The projections were 0.060 in. in diameter by 0.012 in. high, and the holes in the blade were 0.070 in. in diameter. There was almost no welding of the beryllium copper blade to the steel supports.

The electrodes were 5/8 in. in diameter with type C (flat) faces, and were made of class 1 material. Two locating pins, made of an electrically nonconductive material and fitted into the lower electrode, passed through matching holes and notches in the workpieces (see Fig. 7) to provide positive location of the assembly. The upper electrode had matching clearance holes for the locating pins.

In operation, the three workpieces were placed on the lower electrode over the two locating pins with the blade between the two steel supports. The welding machine was then actuated to make the weld, and simultaneously a magnetic force system was actuated to forge the weld metal. The forging force closed the gap between the steel supports and expanded the plastic metal against the holes in the blade. The assemblies made in this way proved completely satisfactory, and in service, the silver contact on the blade (see Fig. 7) was worn away before the blade failed in the weld area; failure, if any, occurred elsewhere in the blade.

Five welded assemblies were peel tested by an inspector during each hour. In this test the two steel supports were peeled apart, and it was required that a nugget be pulled from one of the steel supports at each weld.

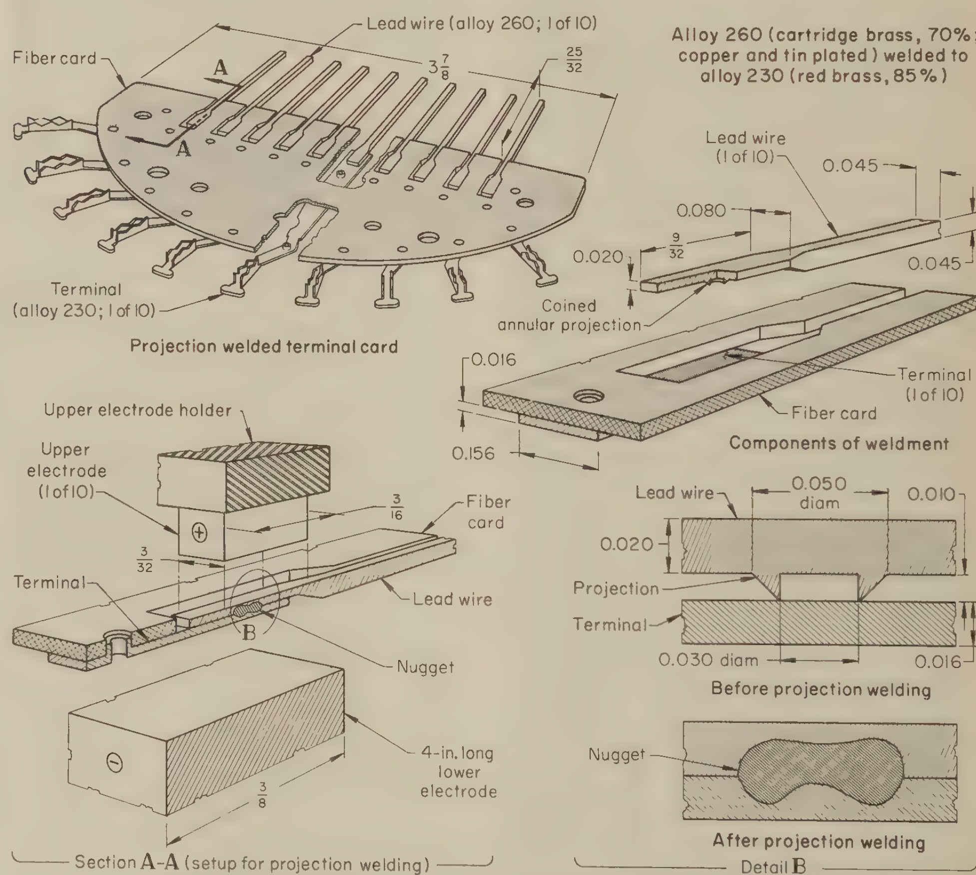
Additional equipment details and welding conditions are given in the table that accompanies Fig. 7. All welding machines in this group had individual connections to a central exhaust system. A flexible tube was located adjacent to the weld area to remove any hazardous fumes and to prevent them from reaching the operator or the adjacent areas.

Low-Zinc and High-Zinc Brasses

The low-zinc brasses are difficult to weld, although easier than copper, and are subject to electrode pickup. Welds made in these brasses may lack strength, principally because of comparatively high electrical conductivity (32 to 56% IACS).

The high-zinc brasses have an electrical conductivity of 27 to 28% IACS and can be both spot and projection welded over a wide range of conditions. Electrode pickup can be a problem unless weld time, welding current and electrode force are properly selected.

Excessive electrode pickup and blowthrough of the weld may occur when long weld times, high energy input and low electrode forces are used. Yellow brasses (alloys 268 and 270) are less subject to electrode pickup than car-



Equipment Details

Welding machine	440-v ac automatic press type, with ten welding heads and ten transformers
Rating at 50% duty cycle	20 kva each
Rating of secondary circuit	4.6 to 6.1 v, 2000 to 4000 amp
Electrodes	RWMA class 2(a)
Controls	Synchronous, with sequential firing
Auxiliary equipment	Indexing table(b)

Conditions for Projection Welding

Welding current	2000 amp, ac
Welding voltage	5 v
Electrode force	50 lb
Squeeze time	5 cycles, min(c)
Weld time	1 cycle
Hold time	5 cycles, min(c)
Production rate:	
Assemblies per hour	1100
Welds per hour	11,000

(a) Ten upper electrodes, 3/32 by 3/16 in.; one lower electrode, 3/8 by 4 in. (b) 24-stop rotary table. (c) Squeeze time and hold time varied because the upper-electrode holders were attached to the press ram, and times were determined by mechanical motions of the ram.

Fig. 8. Cartridge brass lead wires and red brass terminals that were joined by projection welding, instead of by spot welding, to prevent electrode sticking, using annular projections designed to limit expulsion of weld metal (Example 427)

tridge brass, except when long weld times and high energy input are used. Electrode force should be sufficient to prevent arcing or expulsion of molten metal, to which these alloys are subject because of their 30 to 40% content of zinc, which boils at about 1665 F. As shown in Table 2, the recommended electrode force, when using electrodes having a face diameter of $\frac{3}{16}$ in., is approximately 400 lb.

For weldability ratings, see "Welding index" entries in Table 1.

In projection welding, the projections should be as small as practicable, especially the height. A short weld time and a low-inertia welding head with fast electrode follow-up should be used. Tin plating the workpieces generally will improve weld quality, although expulsion of molten tin from the weld interface may occur.

In the example that follows, in which cartridge brass lead wires were welded to red brass terminals, heat balance was obtained by flattening the wires, which were square in cross section and thicker than the terminals. Spot welding was replaced by projection welding so that large electrodes, which would not stick to the work metal, could be used. Projections that were carefully designed to trap weld metal and limit expulsion were coined on the flat section of the wire.

Example 427. Use of Projection Welding With Annular Projections To Eliminate Electrode Sticking and To Limit Expulsion of Weld Metal (Fig. 8)

A cartridge brass lead wire was joined to a red brass terminal by resistance projection welding as shown in Fig. 8. The terminal was 0.016 in. thick, and the lead wire was 0.045 in. square and was plated with 0.0002-in.-thick copper and with 0.0002-in.-thick tin over the copper. The end of the cartridge brass lead wire was flattened to 0.020 in. thick by 0.080 in. wide by $\frac{9}{32}$ in. long, and an annular projection was coined on one surface. Coining, rather than forming, produced a projection that was strong enough to withstand the electrode force used without collapsing prematurely. The annular projection was designed to prevent expulsion of molten metal.

Originally, the 0.045-in.-sq lead wire was resistance spot welded to the terminal without flattening the end of the wire. Spot welding was not successful, and electrode pickup from the cartridge brass wire was excessive because of the small area of contact between the electrode and the work metal.

Projections of several shapes, including a transverse bead and a longitudinal bead, were tried before the annular projection shown in Fig. 8 was developed. Besides allowing excessive expulsion of weld metal, the transverse bead had to be at the center of the electrode to prevent tilting of the workpiece and contact of workpiece surfaces elsewhere than at the projection. (Circular, square and cross-shape projections provide much more stability than bead-type projections.) The longitudinal bead also caused excessive expulsion of work metal because the volume of weld metal was too great and melting was erratic and inconsistent.

The annular projection had a steep internal slope (about 90°) and a 45° external slope so that, as the projection melted, the molten metal was confined by the remaining metal of the projection.

The welds were made in an automatic welding machine that had a 24-stop rotary-indexing table and ten welding heads, each with a 20-kva transformer. Electrode material was class 2. The lower electrode was made in one piece and was connected to the negative terminals of the transformer secondary circuits. Each of the ten upper electrodes was mounted to a welding head and was connected to the positive terminal of a transformer.

Ten red brass terminals were permanently mounted on a fiber card, and were degreased and cleaned with a rotary wire brush after the card was placed on the indexing table. The cartridge brass wires were cleaned and lubricated by wiping with a felt pad as they were fed into the flattening, coining and cutoff die. In the welding position, the flattened end of each of ten cartridge brass square wires extended beyond a wire-guide groove in the die and over one of the ten terminals fastened to the fiber card. A notch in the card at each terminal helped to position the lead wire. The ten welding transformers had synchronous controls and were fired in sequence.

The equipment for this operation cost about $80,000; cost of replacing electrodes was minor. Equipment details and welding conditions are given in the table that accompanies Fig. 8.

The use of projection welding offers several advantages for the joining of high-zinc brasses, which is often done with close weld spacings and edge distances. The projection defines the size and location of the weld. There is no marking of the parts from electrodes that are misaligned, too large in diameter or have improper face shape. Distortion and sticking of electrodes are minimized because a relatively large area of the workpiece is in contact with the projection welding electrode. Also, localized heating produces a minimum decrease in the hardness and strength of the base metal. Projection welding also permits multiple welds to be made simultaneously at a closer spacing than is possible with spot welds, as is illustrated in the following example.

Example 428. Projection Welding a Cartridge Brass Terminal to a Narrow Phosphor Bronze Blade (Fig. 9)

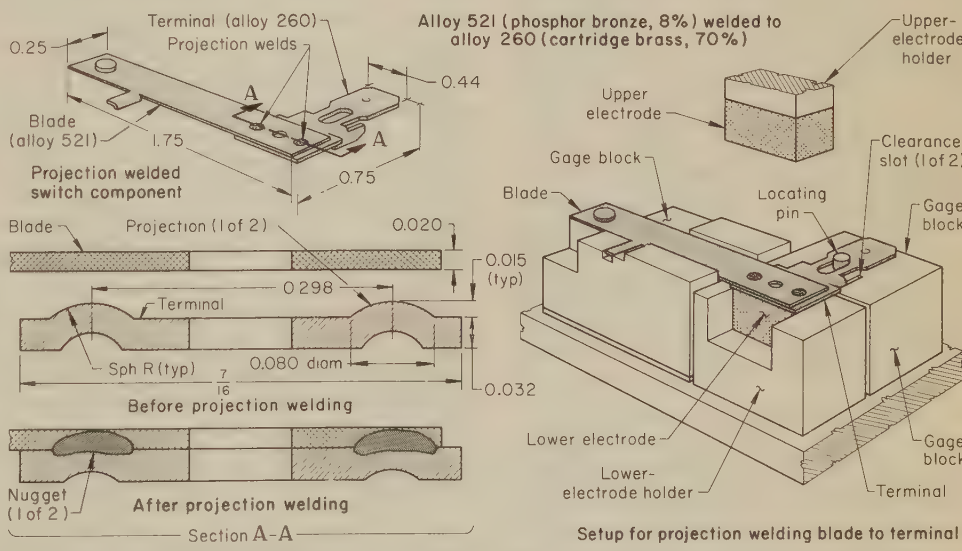
The switch component shown in Fig. 9 was made by projection welding an alloy 260 (cartridge brass, half hard) terminal to an alloy 521 (phosphor bronze, spring temper) blade. The low electrical conductivity of these alloys (28% IACS for alloy 260 and 13% for alloy 521) made them relatively easy to join by resistance welding. Two welds were used for joining the terminal and the blade, and the use of projection welding allowed closer spacing of the welds than normally allowed by spot welding, and made both welds simultaneously.

The terminal, with two spherical projections 0.080 in. in diameter by 0.015 in. high and spaced at 0.298 in., was made in a progressive die. The blade was a flat strip with a hole at one end and a contact fastened to the other end. The slot in the terminal was used for locating the part during projection welding. Before welding, both parts were degreased and bright dipped, then carefully rinsed.

The electrodes were made of refractory metal compositions (RWMA group B) to reduce electrode pickup, and were rectangular in shape, which made them easy to clean and replace. The upper electrode was made of class 13 material (tungsten) and the lower electrode was made of class 11 material (a mixture of copper and tungsten). Both electrodes were fastened to holders made of class 2 material. A gage block supported and located the blade, and a pin located the terminal during welding.

Copper Nickels

The copper-nickel alloys have electrical conductivities of 4.6 to 9% IACS, are readily spot and seam welded with relatively low welding current, and generally do not alloy with the electrode material and cause electrode pickup. Proper preweld cleaning is required to ensure low and consistent contact resistance. Short weld times prevent electrode indentation.



Equipment Details

Welding machine	440-v single-phase ac press type, with synchronous controls
Rating at 50% duty cycle	30 kva
Current, max	22,500 amp
Upper electrode	RWMA class 13
Lower electrode	RWMA class 11
Electrode holders	RWMA class 2
Electrode force, max	750 lb

Conditions for Projection Welding

Welding current	19,200 amp, ac
Secondary voltage	6 v
Electrode force	180 lb
Squeeze time	20 cycles
Weld time	3 cycles
Hold time	5 cycles
Production rate:	
Assemblies per hour	750
Welds per hour	1500

Fig. 9. Switch component that was made by joining a cartridge brass terminal to a phosphor bronze blade, in the setup shown, using closely spaced projection welds (Example 428)

Nickel Silvers

Nickel silvers, which have about the same conductivities as copper nickels, are spot welded as readily as copper nickels (see Table 1), but are more difficult to seam weld. Surface contaminants such as lead and bismuth (which form low-melting eutectics with copper and nickel) or sulfur (which may be introduced in forming) must be removed before resistance welding.

Although cold worked base metal is softened by welding, postweld heat treatment is seldom used except when needed for corrosion resistance.

Bronzes

The phosphor bronzes, except alloy 505, which is not recommended for resistance spot and seam welding, have relatively low electrical conductivity (10 to 15% IACS) and are readily spot and seam welded using low welding currents. Electrode pickup can be reduced by use of a type F (radius) electrode face and frequent redressing to keep the face clean and smooth. Hot shortness can be minimized by supporting the workpieces to prevent strain during welding and by using a greater minimum overlap than recommended by the data in Table 3.

Projection welding of phosphor bronze alloy 521 to alloy 260 (cartridge brass) is described in Example 428. Location of the spot weld with respect to the edge of the workpiece was a factor in preventing expulsion of weld metal in Example 408, in the article on Resistance Welding of Stainless Steel, in which a spring made of copper alloy 510 (phosphor bronze, 5% A) was spot welded to a U-shape workpiece made of type 304 stainless steel.

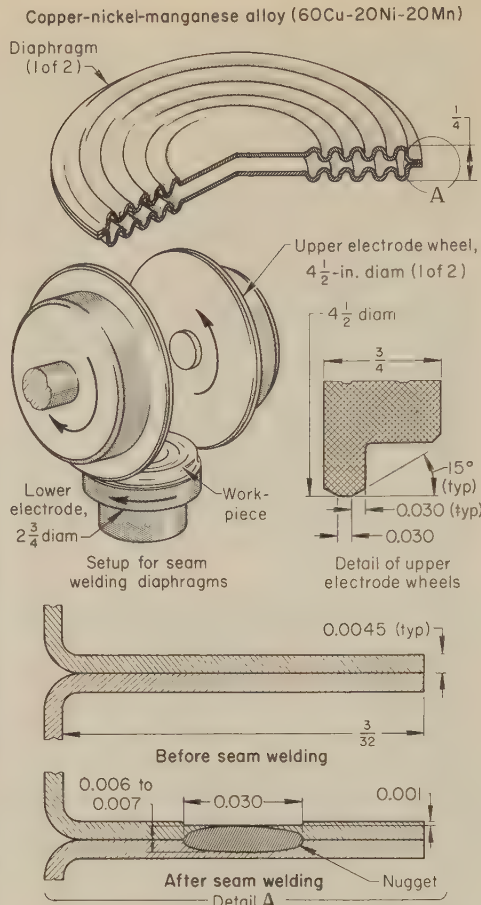
Silicon bronze alloys (7 to 12% IACS conductivity) are the most easily resistance spot and seam welded of all copper alloys. Low welding current and low electrode force (see Table 2) usually are required. Short weld times should be avoided, to prevent shrinkage voids. The surface oxides that develop during annealing must be removed to ensure low and consistent surface contact resistance.

Resistance welding of aluminum bronze is similar to resistance welding of silicon bronze, but with much more electrode pickup and expulsion of weld metal, which can be controlled by careful adjustment of weld time, welding current and electrode force.

Special-Purpose Alloys

Leaded alloys are generally more difficult to weld than those without lead. Poor weld strength, fracturing of metal during welding, and bleeding or fuming of lead from the weld nugget are the major problems.

The copper-nickel-manganese alloy listed in Table 1 has mechanical properties similar to those of alloy 172 (beryllium copper), and both can be precipitation hardened to a tensile strength greater than 150,000 psi. The low electrical conductivity of the copper-nickel-manganese alloy makes it easier to resistance weld than many other copper-base alloys. In the example that follows, this alloy was used as the work metal because it could be resistance seam welded more easily than beryllium copper.



Equipment Details

Power supply	220 v, single-phase, ac
Welding machine	Resistance seam, with two welding heads connected in series
Rating at 50% duty cycle	30 kva
Current, max	21,450 amp
Upper electrodes (2)	4½-in. diam by ¾ in. thick, RWMA class 3
Lower electrode	2¾-in.-diam rotating nest RWMA class 3
Electrode force, max	800 lb per head

Conditions for Resistance Seam Welding

Welding current	1600 amp, ac
Welding voltage	3.5 v
Heat time	2 cycles
Cool time	2 cycles
Welding speed	30 in. per minute
Production rate	120 to 150 assemblies per hr

Fig. 10. Two 0.0045-in.-thick diaphragms, made of a copper-nickel-manganese alloy, that were joined by resistance seam welding to produce a pressure-sensing capsule (Example 429)

Example 429. Resistance Seam Welding of Two 0.0045-In.-Thick Diaphragms Made of a Copper-Nickel-Manganese Alloy (Fig. 10)

A gastight joint around the edge of the capsule shown in Fig. 10 was used to seal the capsule hermetically so that it could be used as the sensing member in an aneroid barometer. The capsule was composed of two diaphragms 0.0045 in. thick arranged so that they would react to any change in external air pressure.

The diaphragms were made of an age-hardenable copper-nickel-manganese alloy (60 Cu, 20 Ni, 20 Mn) with many mechanical properties similar to those of beryllium copper (alloy 172). Beryllium copper was often used for the diaphragms, but because of its higher electrical and thermal conductivities was not suitable for this application, in which the assembly was to be resistance seam welded. The copper-nickel-manganese alloy could be resistance seam welded easily.

Welding was done in a resistance seam welding machine that had two welding heads connected in series with the transformer. The two heads were diametrically opposed and permitted each upper electrode wheel to traverse one half of the circumference of the capsule. Double clamping of the diaphragms against the horizontal rotating-nest lower electrode by the two electrode wheels kept the diaphragms from shifting during seam welding, and therefore made tack welding unnecessary. Alcohol was used for cooling the work metal; water would have been difficult to evacuate from the capsule.

The diaphragms were formed from clean, bright strip; drawing lubricants were removed by vapor degreasing before welding. The welding operation was semiautomatic; the operator loaded and unloaded the workpieces and pressed a button to start the welding machine, which then made a series of overlapping spot welds.

Gas tungsten-arc welding was considered as an alternative process for joining the diaphragms, but was not used. The shorter weld time and the lower operator skill necessary for resistance seam welding were major factors in the choice of that process, as shown in the following comparison of costs per piece.

Cost	Gas tungsten-arc	Resistance seam
Equipment	$0.015	$0.020
Labor	0.050	0.020
Total	$0.065	$0.040

Also, with resistance seam welding, rejects were fewer (less than 1%) and were easier to salvage than if the diaphragms had been joined by gas tungsten-arc welding.

After welding, the work metal in the assembly was age hardened at 700 to 800 F, to a tensile strength of 175,000 psi and a yield strength, at 0.1% offset, of 150,000 psi.

Production rate was 120 to 150 pieces per hour. Additional equipment details and welding conditions are given in the table that accompanies Fig. 10. The relatively large-diameter electrode wheels, with respect to the diameter of the seam weld, allowed a flatter contacting surface and less indentation and distortion of the workpiece than smaller-diameter wheels.

Safety

In resistance welding of copper alloys, a ventilation system may be needed because many copper alloys contain at least small amounts of toxic alloying elements. However, the need for ventilation is less critical for resistance welding operations than for arc welding operations, because a smaller volume of metal is heated and a smaller volume of fumes is generated.

Safety precautions for cleaning and pickling operations are given in the article on Cleaning and Finishing of Copper and Copper Alloys, beginning on page 635 in Volume 2 of this Handbook.

Detailed information and references on safe practices, cautions, contaminants, and hazards in welding are presented in "Safety in Welding and Cutting", American National Standard Z49.1, American National Standards Institute, Inc., 1430 Broadway, New York, N. Y. 10018 or American Welding Society, 2501 N.W. Seventh Street, Miami, Fla.

FLASH AND FRICTION WELDING

CONTENTS

Flash Welding

*By the ASM Committee on Flash, Friction and Stud Welding**

FLASH WELDING is a resistance butt welding process in which two workpieces are clamped in suitable current-carrying fixtures that hold them end-to-end in very light contact. An electric potential is applied that causes current to flow through the workpieces to produce flashing, or arcing, that, in combination with electrical resistance, heats the abutting ends to the fusion point. When the abutting ends reach the proper temperature, the workpieces are suddenly brought together with force sufficient to cause an upsetting action. Upsetting forces plastic metal, together with most of the impurities not expelled by flashing, out of the joint.

Applications. In the aerospace industry, flash welding is used in the production of solid and tubular structural assemblies, landing gears, and rings of various sizes. Wheel rims, headlight rims, frame siderails and control-mechanism linkages are typical of automotive parts commonly joined by flash welding. Other applications include welding of window frames in the automotive and building industries, welding of band-saw blades into continuous loops, and joining of tool steel drill, tap and reamer bodies to low-carbon steel and alloy steel shanks.

The largest flash welding machines are used in the production of line pipe. Machines with capacities of 6000 kva, capable of delivering over one million amperes, are used to weld 40-ft-long longitudinal joints in pipe up to ⅝ in. in wall thickness, in one operation. The pipe is formed from plate in U-bending, crimping and closing presses. The joint is positioned with the aid of locating lugs, and then the entire length is flash welded simultaneously.

Flash welding machines are used in steel-mill pickling lines, cold reduction lines and re-coiling lines to join coils for continuous operation. In wire mills, flash welding is used to produce coils of specified weights. In both steel mills and wire mills, the welded joint is subject to the same reduction as is the base metal, as in Example 446.

Process Capabilities

Any metal that can be forged can be flash welded, and by careful control of welding conditions, many combinations of dissimilar metals can be joined.

Flash welding can be used to produce assemblies that otherwise would require more costly forgings or castings. The process is capable of producing welds with strength equal to, and sometimes greater than, that of the base metal, of joining a wide variety of similar and dissimilar metals in many different cross-sectional shapes, and of maintaining with high accuracy the length and alignment of workpieces.

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Robert J. Gasser, Manager, Resistance Welding Systems, Sciaky Bros., Inc.; John C. Jenkins, Manager, Application Development Dept., Nelson Stud Welding Co.; Ivar W. Johnson (retired), formerly Metallurgist, Knolls Atomic Power Laboratory, General Electric Co.; C. D. Loyd, Supervisor, Materials Div., Engineering General Office, Caterpillar Tractor Co.; G. W. Reeder, Chief Metallurgist, American Welding & Manufacturing Co.

W. C. Rudd, Director, AMF Thermatool, Inc.; A. L. Williams, Manager of Engineering, Welders and Presses, Wean Industries, Inc.; W. F. Williams, Equipment Engineer, Buick Motor Div., General Motors Corp.; A. C. Young, Pressure Weld Engineer, Power Transmission Div., General Electric Co.

Most of the examples presented in this article were contributed by members of other Metals Handbook welding committees. The assistance of Taylor-Winfield Corp. also is gratefully acknowledged.

Welds can be made with the longitudinal axes of the workpieces either in line with each other, or at an angle, as in a miter joint.

Generally, the finish or shape of the abutting surfaces is not critical — except on large workpieces, where the ends are beveled to initiate flashing and to promote expulsion of the flashing particles (see Example 435). For welds of high quality, the two ends to be welded should be similar in size and shape.

Economy in Operation and Material. Flash welding is economical both in operation and in use of metal. In applications where flash welding has replaced other joining processes, the production rate has been substantially increased. For instance, in Example 448, the production rate was increased from 144 to 275 welds per hour when torch brazing was replaced by flash welding. In Example 450, the over-all cost of producing steel rings was reduced 19% by changing from gas tungsten-arc welding to flash welding.

Flat or extruded bars of metal are rolled into rings of proper dimensions, which are then flash welded into continuous rings. When rings are produced in this way, less metal is lost by machining than when rings are forged, and less scrap loss is incurred than when rings are cut from plate. The flash welded joint has strength nearly equal to that of the base metal, and generally can be either hot or cold worked in the same manner as can the base metal.

In joining forgings to tubing, material costs and the weight of assemblies can be minimized by using flash welding, as in Example 431.

Weld Strength. With postweld heat treatment, high-quality welds in steel can be produced that are almost as strong as the base metal, even when the weldments are heat treated to a tensile strength of as much as 200,000 psi, for 4130 steel, or 240,000 psi, for 4340 steel. Components that are made of heat treatable steels generally are welded in the annealed condition and are then normalized, quenched and tempered after welding. Flash welding affects or removes any cold worked properties.

Fatigue properties of flash welded joints, after the weld upset is removed, generally are equal to or better than those of joints made by other welding processes. (See the sections in this article on The Heat-Affected Zone, page 498; Hardness of Welds, page 499; and Strength of Welds, page 501.)

Table 1. Maximum Cross-Sectional Areas, and Required Welding-Machine Capacities, for Flash Welding Various Work Metals

Work metal	Maximum area, sq in.	Capacity of welding machine: Kva	Tons
Carbon and low-alloy steels	60	1500	750
Modified 4340 alloy steel ..	33	1600	500
Series 300 stainless steels ..	40	1600	500
Series 400 stainless steels ..	22	1600	500
Heat-resisting alloys	25	1600	500
Maraging steel, 18% Ni	15	1600	500
Nickel alloys	25	1600	500
Aluminum alloys	14	1600	500
Titanium alloys	40	1600	500

Sections Welded. A wide variety of cross-sectional shapes can be flash welded, including flat strip, sheet, tubing, bar and plate stock, forgings, extrusions and many combinations of these product forms.

Accuracy. With proper fixturing, the alignment of the welded parts can be held well within the requirements of MIL-W-6873. According to this specification, the maximum mismatch or eccentricity between the welded parts must not exceed 10% of the sheet or tube-wall thickness, and must not exceed 0.008 in. when sheet or tube-wall thickness is 0.080 in. or less. In addition, the angular misalignment (straightness) of the welded parts must not exceed 0.005 in. per inch of length.

The tolerance on the welded length can be less than the sum of the tolerances on the individual parts when proper locating tooling and welding-machine setup are used. There are no uniform standards for tolerances on welded length, and practices vary widely. In general, the tolerance on the welded length is affected by four factors: (*a*) the tolerances on the individual parts, (*b*) the allowance for dimensional changes during heat treating, (*c*) the amount of machining after welding, and (*d*) the care used in loading and locating the parts in the welding machine.

Disadvantages and Limitations

One of the most undesirable features of flash welding is the flashing operation itself, during which molten particles of metal are expelled rapidly from the weld region. It is impossible to protect the welding machine and the surrounding area from these particles, which can burn into slideway bearings, insulation and other critical machine parts. Periodic disassembly of the machine and replacement of insulation and bearings are part of normal maintenance procedure.

Flash welding also presents a considerable fire hazard. Operators must be protected from the flying particles, combustible materials must be kept away from the welding machine and its surrounding area, and a fire-resistant grade of hydraulic oil should be used in the machine.

Removal of the flash and upset metal generally is necessary, and requires additional machinery, such as a flash-and-upset trimmer, and thus adds to the cost of the product. Removal of weld upset from flat workpieces is simple, provided that the mating parts are of equal thickness or cross section; removal of weld upset from contoured workpieces must be done by hand grinding or by chipping. Upset on the inside of butt welded pipe or tubing can restrict fluid flow, reduce fatigue strength, and serve as a point of concentration for corrosion or contaminants. Upset is difficult or impossible to remove from the inside of small-diameter pipe or tubing.

Concentricity and straightness of workpieces during welding is often difficult to maintain, and misalignment can cause rejection or can necessitate postweld machining operations.

Another disadvantage of flash welding is the cost of providing stock to compensate for the metal lost during flashing and upsetting.

Limitations. The size and cross-sectional area of workpieces that can be flash welded are limited by the power and upsetting force available in the machine. Workpiece size is sometimes limited by maximum clamp travel and maximum opening between clamping surfaces. Table 1 gives typical maximum cross-sectional areas, and required welding-machine capacities, for flash welding various work metals.

If a sound flash weld is to be made, the abutting ends should be of essentially the same size and shape. Considerable difficulty is encountered if the cross sections are unequal. (See the section on Heat Balance Between Workpieces, page 494.) In welding extrusions that have different shapes, generally the nonmatching portions must be cut away (see Example 434).

When a small-diameter ring is flash welded, current is shunted around the ring. If shunting becomes excessive, the flashing voltage cannot be maintained and a weld of good quality cannot be made. The welding of small-diameter rings is also complicated by the difficulty of clamping and aligning the flashing surfaces.

Flash welding of T-joints is generally limited. For instance, when the end of a round tube is flash welded to the side of another round tube, the differences in section, heat balance, and resistance to the upsetting force usually result in a weld of poor quality.

In the region of contact with the clamping dies, the surfaces of scaly, rusty, oxidized or otherwise coated workpieces must be cleaned before being flash welded, to ensure proper current flow. On aluminum alloys, which require high welding current, surface coatings such as oxide, paint, oil and anodized films can cause localized hot spots. These hot spots can cause overheating of the clamping dies,

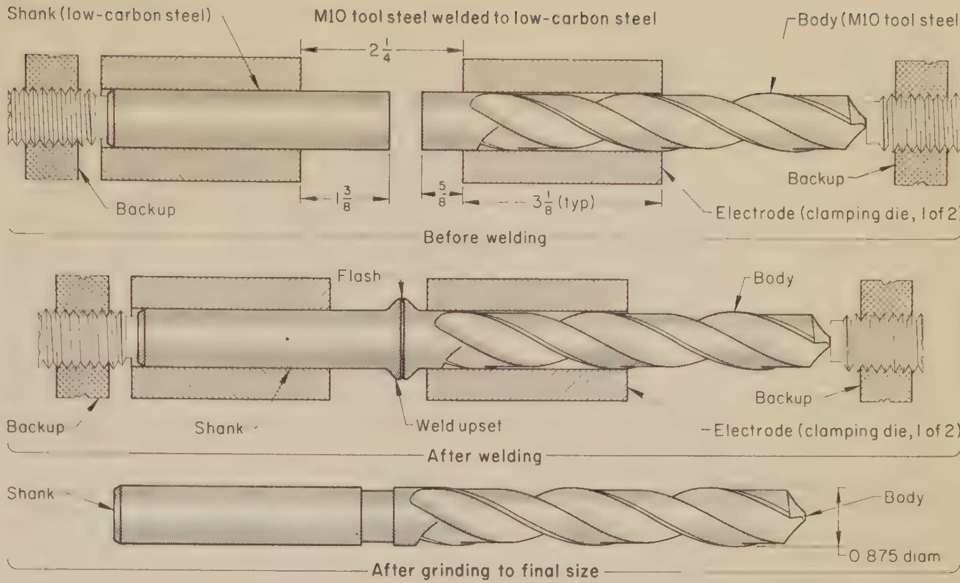
Table 2. Some Combinations of Base Metals That Have Been Flash Welded

Base metal	Metals that have been flash welded to base metals listed in the first column: Aluminum alloys	Copper alloys	Magnesium alloys	Molybdenum	Nickel alloys	Steels, carbon and alloy	Steels, stainless	Steels, tool	Tantalum	Titanium alloys	Tungsten
Aluminum alloys .	X	X	X	...	X	...	...	...	...	...	...
Copper alloys	X	X	X	...	X	X	X	X	...	X	...
Magnesium alloys.	X	X	X	...	...	...	...	...	...	...	...
Molybdenum	...	X	...	X	X	X	X	X	...	...	...
Nickel alloys	X	X	...	X	X	X	X	X	X	...	X
Steels, carbon and alloy	...	X	...	X	X	X	X	X	X	X	X
Steels, stainless ..	...	X	...	X	X	X	X	X	X	X	X
Steels, tool	...	X	...	X	X	X	X	X	X	...	X
Tantalum	...	X	...	...	X	X	X	X	X	...	...
Titanium alloys ..	...	X	...	...	...	X	X	...	...	X	...
Tungsten	...	...	...	...	X	X	X	X	...	...	X

or melting of sections of the dies or workpieces.

Alignment of workpieces made of thin stock, either tubular or flat, sometimes is difficult. If dies are not carefully maintained, poor alignment of the workpieces results and flashing occurs only at the points of contact. During upsetting, the workpieces slip past each other, resulting in a lap instead of a weld. Subsequent trimming may remove the welded region and cause separation.

In flash welding of mitered corners, the shapes of the workpieces may prevent adequate clamping that would ensure a good weld. In many aluminum window frames made from extruded sections, the jamb, header and sill sections are different. In most mitered joints, acceptable welds can be made in legs that, in welding position, are in the same plane as the direction of the upsetting force or platen movement, but poor welds are made in legs that are not in the plane of platen movement. Often, legs not in the plane of platen movement are cut away so that they do not flash or upset. The amount cut away can be such that the legs are in good mechanical contact after the workpiece has been flash welded.



Equipment Details	
Welding machine	220 v, single phase(a)
Transformer rating	100 kva
Welding current, max	67,500 amp at 6.28 v
Clamping-die material	RWMA class 4

Welding Conditions	
Initial die opening	2¼ in.
Final die opening	1½ in.
Initial gap	¼ in.
Initial extensions:	
M10 steel	⅝ in.
Low-carbon steel	1⅜ in.
Final extensions:	
M10 steel	⅜ in.
Low-carbon steel	1⅛ in.
Total metal lost	½ in.
Preheat time(b)	3 sec
Flashing time(b)	4 sec
Upsetting time(b)	1 sec

(a) With air-actuated clamping force, manual platen movement, and platens inclined at 35°. (b) All three times are approximate because platen movement was actuated manually.

Fig. 1. High speed tool steel drill body and low-carbon steel shank that were joined by flash welding, then ground for upset removal and final sizing (Example 430)

Metals Welded

Flash welding can be used for joining many ferrous and nonferrous alloys, and combinations of dissimilar metals. In addition to low-carbon steel, metals that are flash welded on a production basis include medium-strength and high-strength low-alloy steels, tool steels, austenitic, martensitic and ferritic stainless steels, aluminum alloys, copper alloys, magnesium alloys, molybdenum alloys, nickel alloys and titanium alloys.

When carbon and alloy steels of high hardenability are flash welded, the as-welded properties of the heat-affected zone deviate substantially from those of the base metal, and postweld heat treatment is necessary to obtain uniformity of properties, especially if the weldment is to be drawn or reduced in section. Heat treating in the welding machine is unlikely to have the proper metallurgical effect. Sometimes the required heat treating process involves a longer heating and cooling cycle than is possible in the welding machine.

Cast iron has never been satisfactorily flash welded in production, although some acceptable results have been achieved in the laboratory.

Low-carbon steels are readily flash welded without preheating. As the carbon and alloy contents increase, preheating or postheating, or both, may be necessary for maximum weld quality. Required upsetting pressure for welding various types of steel is related to the forging strength of the steel at elevated temperatures and to the temperature gradient in the steel in the upset area. Most types of steel are readily welded in both similar and dissimilar combinations, but some combinations require special procedures.

Aluminum alloys are generally flash weldable, but the stock thickness should be greater than 0.050 in. Aluminum extrusions are readily flash welded, but may need special attention at the abutting surfaces (see the section in this article on Miter Joints, page 497).

In general, copper alloys with a high zinc content weld better than those with a low zinc content; the high-leaded copper alloys may give brittle welds. The ductility of welds in some copper alloy rods allows the rods to be flattened under repeated hammering to approximately 15% of the original thickness without indications of fracture at the weld.

Flash welding of lead, zinc, tin, bismuth and antimony, and alloys of these metals, is impractical.

Toxic metals, such as beryllium and beryllium alloys, are not suitable for flash welding without stringent precautionary measures to prevent contamination of air and equipment and danger to personnel by flash particles and dust.

Many combinations of dissimilar metals are easily flash welded if the proper welding conditions and workpiece design are used. Table 2 lists some combinations of metals that have been joined by flash welding.

A common application of flash welding dissimilar metals is the manufacture of large-diameter taps, drills and reamers. A low-carbon or alloy steel shank is welded to a high speed tool steel body to conserve the more expensive tool steel and to provide a soft, tough shank. The following example describes the manufacture of a drill by flash welding a carbon steel shank to a tool steel body.

Example 430. Low-Carbon Steel Shank Flash Welded to an M10 Tool Steel Drill Body (Fig. 1)

The 0.875-in.-diam drill shown in Fig. 1 was made by flash welding a low-carbon steel shank to an M10 high speed tool steel body. This technique conserved the more expensive tool steel and provided a soft, tough shank for insertion into the spindle of the drilling machine. Before welding, the tool steel body was fluted, pointed and hardened. After welding, the weld upset was removed, and the shank and drill body were brought to final size, by grinding.

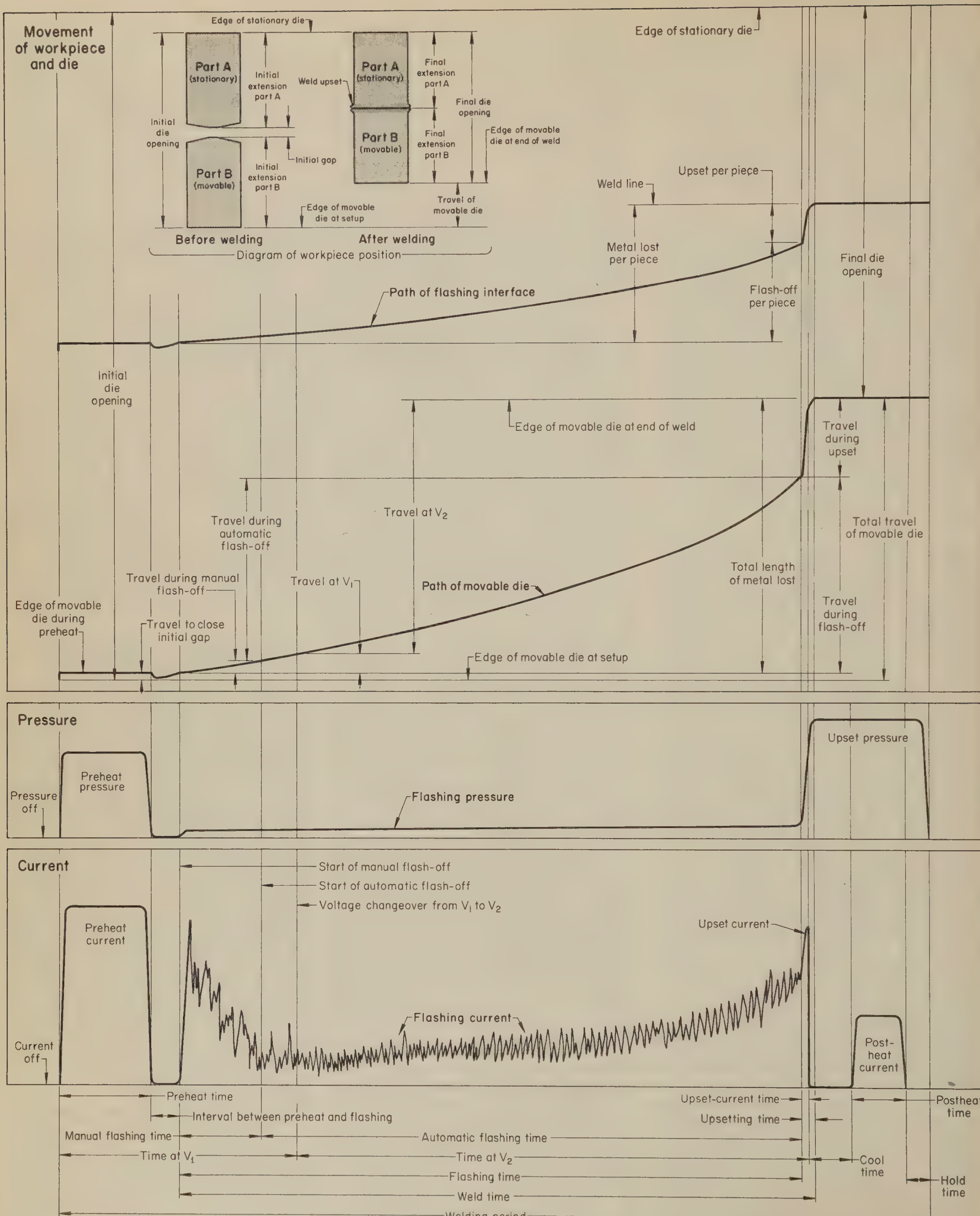
The 3⅛-in.-long air-operated clamping dies were made from RWMA class 4 material (a beryllium-copper alloy having a nominal composition of 1.8% beryllium, 0.3% cobalt, remainder copper; an average electrical conductivity of 18% IACS; and a hardness of Rockwell C 33). Fixtures incorporating backups were fastened to each platen to prevent slippage of the shank and drill body in the clamping dies during upsetting. The platen was moved manually during preheating, flashing and upsetting. Total weld time was about 8 sec.

The platens on the welding machine were inclined at an angle of 35°. This made the welding machine easy to load, and gave the operator full view of the welding operation.

Equipment details and welding conditions are given in the table with Fig. 1.

Fundamentals of the Process

The heat for flash welding is generated by rapidly recurring short circuits of high electrical current at the abutting ends of the workpieces to be welded. The weld is produced by the application of a forging force as the workpiece reaches welding temperature. The upsetting force is produced either manually through lever action, me-



This illustration is intended to define the variables in flash welding. The relationships of the variables to each other do not indicate intrinsic values, and not all functions shown here are used on every flash welding machine or for every flash welding operation.

Fig. 2. Typical flash welding cycle, showing relations of variables and workpiece position before and after welding

chanically through a motor-driven cam, or hydraulically through hydraulic cylinders. The two workpieces are firmly secured by two sets of clamping dies that conduct the welding current. One set of clamping dies is mounted on the movable platen and the other on the stationary platen of the welding machine.

The process is started by bringing the ends of the workpieces into light contact to establish a flashing action. The irregular localized contact between the two lightly touching surfaces results in an extreme localization of heat at the adjoining surfaces. The contact area consists of a series of small short-circuiting contacts in the form of bridges of metal between the two workpieces. These bridges of metal are repeatedly raised to the melting point, broken, and blown out in the form of sparks. This generates the heat necessary to bring a small zone behind the molten surfaces to a temperature within the plastic range.

The movable platen, on which one of the workpieces is held, is advanced to bring new points into contact as metal is expelled during flashing, and continues to move forward toward the stationary platen until the flashing action is continuous over the abutting surfaces. To maintain this flashing, the rate of feed must be properly proportioned to the welding voltage and current. If feeding is too slow, flashing is weak and insufficient heat is generated. If feeding is too fast, the two workpieces stick together prematurely and, if not pulled apart, are joined in a poor weld.

When the correct depth of metal is heated to the plastic range, the speed of the moving platen is suddenly increased, bringing the pieces together under an upsetting force and producing a forged weld. The upsetting action pushes the molten metal, and part of the plastic metal, out of the weld area into a weld upset. In many applications, the upset must be removed after welding, by scarfing or machining.

Figure 2 shows variations during a flash welding cycle, as a function of time. The interrelations among the variables do not represent intrinsic values. Not all of the functions or elements shown in the figure are used on every flash welding machine or for every flash welding operation.

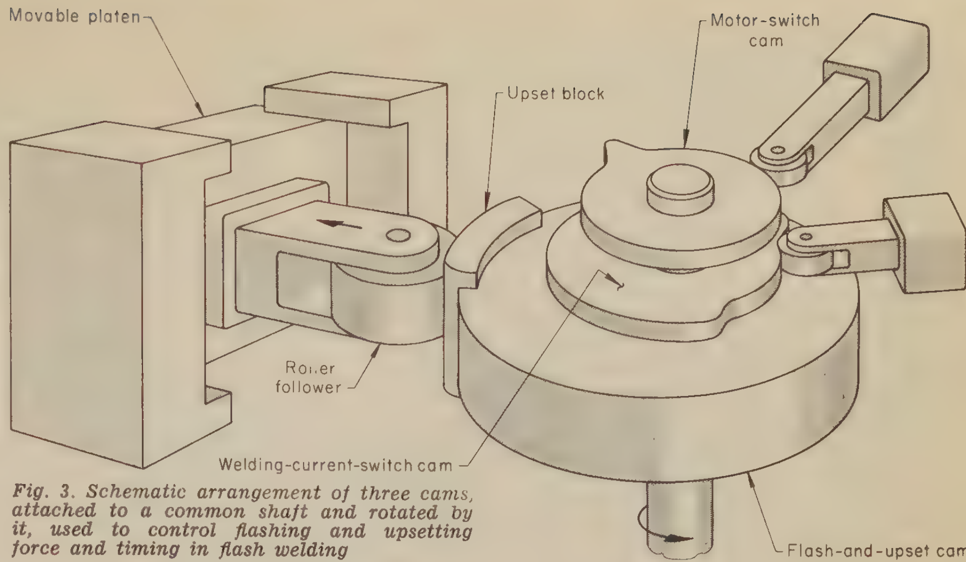


Fig. 3. Schematic arrangement of three cams, attached to a common shaft and rotated by it, used to control flashing and upsetting force and timing in flash welding

Equipment

The machine used for flash welding generally consists of a low-impedance welding transformer, a stationary platen and a movable platen on which the clamping dies, electrodes and other tools needed to position and hold the workpieces are mounted, flashing and upsetting mechanisms, and the necessary electrical, air or hydraulic controls.

Transformer. The transformer is used to supply electrical energy at the voltage and amperage levels needed for the welding operation. The transformer tap switch frequently is a rotary eight-step, knife-type, fully enclosed locking switch, and provides convenient adjustment of the welding voltage to suit the work requirements. Welding transformers are available with primary windings that can be connected either in series or in parallel. This makes the available number of voltage settings twice the number of steps on the tap switch.

Platens. The stationary platen is securely fastened to the machine frame and usually is insulated from it electrically; the insulation is protected from flash and dirt that could cause short circuiting. The movable platen is held in alignment with the stationary platen by bearings and machineways. Stops are provided for quick adjustment of the amount of welding and return travel of the movable platen.

Both platens sometimes are made of a copper alloy such as RWMA class 2 electrode material, and are connected to the transformer secondary by flexible copper bands. Platens are made also of steel or cast iron — frequently with copper alloy inserts. Generally, the clamping dies and electrodes are mounted on the platens. (See page 408 in the article on Resistance Spot Welding for information on classification of RWMA electrode materials.)

Flashing and Upsetting Mechanisms. There are three basic ways of applying the flashing and upsetting forces during flash welding: manually, mechanically through a cam, and hydraulically.

The manually operated mechanism consists of a movable platen operated through a hand-lever-and-toggle arrangement. The toggle mechanism is attached to and insulated from the movable platen. One of the toggle links is a turnbuckle that is used for adjusting the final die opening. The initial die opening is adjusted by a screw-type stop. A pointer on the operating lever indicates on a stationary graduated dial the amount of material that is flashed off and upset. Movement of the lever permits preheating (if desired), flashing and upsetting, in one continuous operation. The operator controls the amount and variation of upset pressure used in the forging action.

A motor-driven cam is used to move the platen when higher production and greater consistency among welds are needed than are possible with manual operation. The cam is operated by the motor through a gear speed-reduction unit with a single-speed or variable-speed drive, or by a variable-speed motor-and-clutch arrangement. Closing and locking of the clamping dies and electrodes are done either manually or by an air or hydraulic cylinder.

Three rotating cams, arranged as shown in Fig. 3, control the operation of the welding machine. Forward movement of the platen is governed by the contour of the flash-and-upset cam, and platen velocity is governed by both the contour and the rotational speed of that cam. The welding-current-switch cam turns the power on and off at the correct time relative to the position of the flash-and-upset cam. The motor-switch cam shuts off the power to the motor or to the clutch at the correct time; this action also is relative to the position of the flash-and-upset cam.

Motor-type flash welding machines are automatic, are the simplest to use, and are predominantly single-purpose, high-production machines without a wide range of flexibility.

When a general-purpose flexible machine is needed that can weld sections requiring more upset pressure than is obtainable with manual or motor-type machines and still can maintain consistency of welds and relatively high production, a machine with hydraulic platen actuation is selected. This machine generally is equipped with hydraulically actuated clamps. Machines with hydraulically actuated platens can be completely automatic, semiautomatic, or manual in operation, depending on how they are adjusted. Completely automatic operation requires little operator skill; semiautomatic and manual operation demand increasing degrees of skill.

Suitability for Application. Different metals have different strengths at flash welding temperature, and in each application the welding current and upsetting capacity of the machine must suit the properties of the metal being welded.

In addition, each machine has mechanical limitations. The clamping space determines the maximum size of workpiece that can be welded, and the clamping-area clearances determine

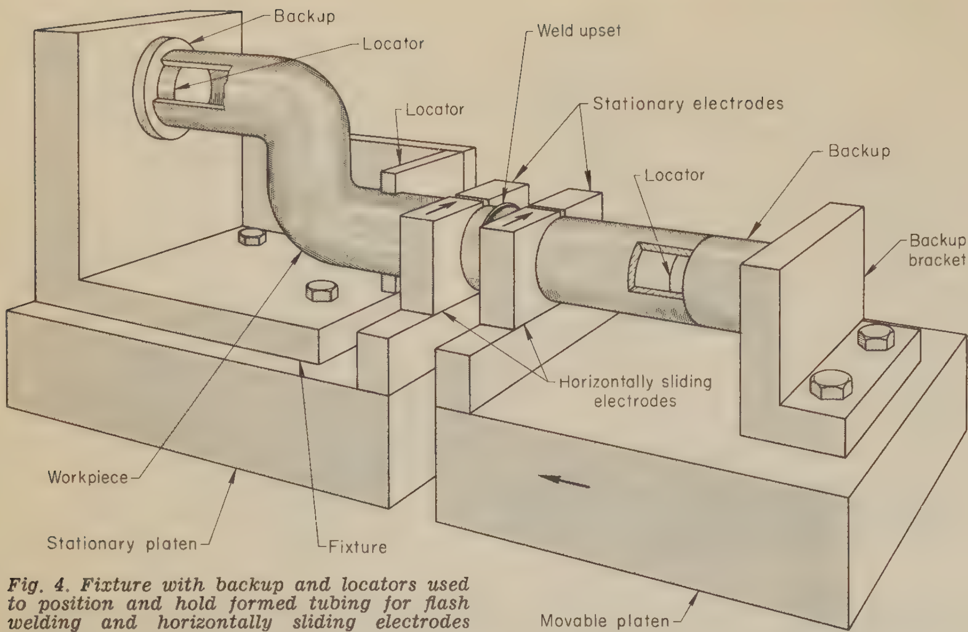


Fig. 4. Fixture with backup and locators used to position and hold formed tubing for flash welding and horizontally sliding electrodes

the size of part or assembly that can be properly clamped. The size and shape of the assembly may not be compatible with the design of the machine. For example, if four tubes are to be welded 90° apart to an X-shape forging, three of the tubes can be welded to the forging with the usual equipment, but a special clamping mechanism with suitable clearance is needed to make the fourth weld.

Clamping Dies and Fixtures

Workpieces must be accurately clamped to maintain alignment, to allow the secondary current to pass into the workpieces, and to apply the upsetting force properly. Generally, the parts of the clamping mechanisms that actually grip the workpieces are the electrodes, often called clamping dies. Fundamentally, the clamping mechanisms allow the dies to move in either the horizontal or the vertical direction. If the clamping dies move in a straight or curved line nearly parallel to the plane of the platen top, the dies are designated as horizontal. If the dies move in a straight or curved line at right angles to the plane of the platen top, the dies are designated as vertical.

In most machines, the principal moving clamping-die member either slides or turns on a pivot. Many workpieces can be welded equally well in either type of clamping die. Pivot-type clamping dies, because of their mechanical advantage, exert more force on the workpiece than do sliding clamping dies.

The use of fixtures, in addition to or in place of clamping dies, is governed by the sizes and shapes of the workpieces, and by the location of features that must be in relation to each other after welding.

Pivot-type clamping dies (or alligator clamps) essentially are levers pivoted in the center; the force is applied at one end, and the clamping-die half is attached at the other end. Because of their circular line of action, pivot-type clamping dies are sensitive to slight variations in stock thickness. This sensitivity is usually decreased by adding a pressure-equalizing mechanism. If an equalizing mechanism is not used, variations in stock thickness will cause variations in the contact area between work metal and electrode, and may damage the contact surfaces because of insufficient area for passage of the secondary current. If one workpiece is clamped incorrectly because it is slightly thicker than the other workpiece, a poor weld can result from the twisting motion that occurs during upset.

When variations in stock thickness are slight, pivot-type clamping dies have an advantage for production purposes, in that workpieces are readily accessible and thus can be easily loaded, positioned and unloaded. Vertically pivoting clamping dies normally are selected for welding joints in sections such as flats and stampings, or for welding small-diameter tubing or solid bars, where current distribution in the work metal permits the transformer to be connected to either the upper or the lower electrodes.

Vertically sliding clamping dies are used where large flat plates or special curved sections are to be welded and, in most applications, eliminate the need for a pressure-equalizing mechanism. With vertically sliding dies, the work is readily accessible, although the high clamping pressure used may require additional apparatus in the form of latches on the open side of the clamping structure.

Horizontally sliding clamping dies usually are selected for welding large solid sections or tubes, into which current must be introduced through all four electrodes. Also, horizontal sliding dies may be used instead of pivoting dies or vertical sliding dies for workpieces that, because of their size or shape, are more easily loaded into the machine from above than from the front side.

Pinch-type dies are used, in welding many nonferrous metals, to contain the heat-affected zone during upsetting and to remove the upset metal. Pinch-type dies have nose inserts (see Fig. 9) shaped to encircle the workpiece and to keep the plastic metal in the weld zone. This minimizes the amount of plastic metal that is extruded out of the weld and, immediately at completion of upsetting, trims any upset that is formed.

Materials for Clamping Dies. Clamping dies or electrodes can be made of any current-conducting metal that is hard enough to withstand the clamping pressures and to resist wear due to scale and oxide on the workpiece. (Best practice is to have the clamping surfaces on the workpiece free from scale, oxide, paint and oil.) When backups are used, the clamping dies generally act only as electrodes and do not resist all of the upsetting force.

The materials commonly used for clamping dies are RWMA class 3, and hardened tool steels such as H11, L6 or O1. (For a description of RWMA classi-

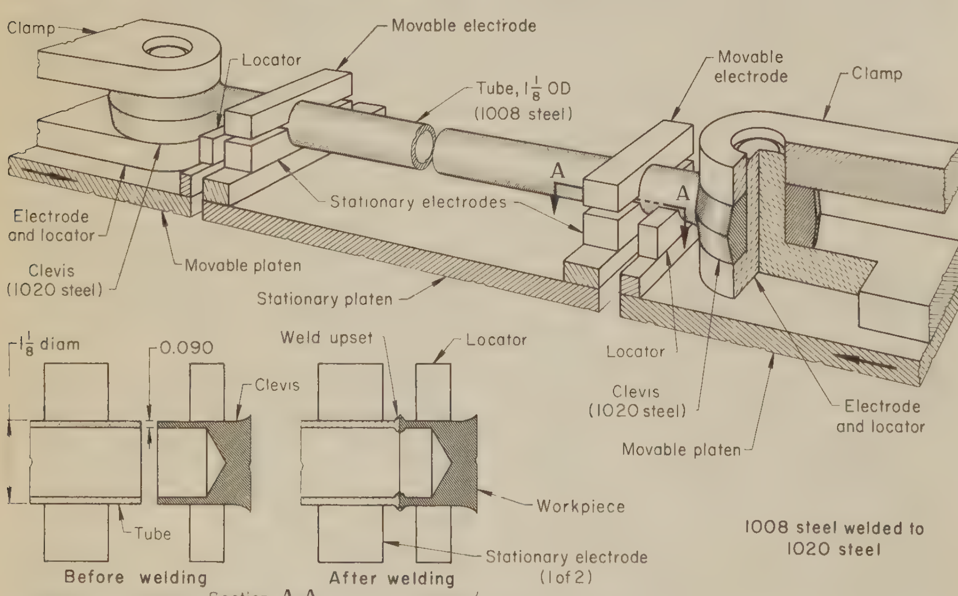


Fig. 5. Setup for simultaneous flash welding of two forged clevises to the ends of a tube, in which a special fixture was used to maintain angular alignment (Example 431)

fications of electrode material, see the section on Electrode Materials, on page 408 in the article on Resistance Spot Welding.) Bronze and other copper-base electrode materials can be used in some applications.

The die half (upper or lower) that carries the current usually is made of a copper-base material. The other half often is made of the same copper-base material, or of hardened steel.

Cooling of Electrodes. The need for water cooling of flash welding electrodes depends on the size of the electrode, die or fixture, the magnitude of the flashing current, and the production rate. When the mass of the electrodes is large compared with that of the workpieces, the heat sink generally is large enough to dissipate the heat generated by the resistance to current flow and the heat absorbed from the workpiece. With high flashing currents and high production rates the electrodes must be cooled.

Electrodes, clamping dies and fixtures used on large flash welding machines usually are water cooled. Those used on smaller machines are less frequently water cooled, unless the flashing current or the production rate is high. Cooling is accomplished by water flowing through internal passages.

Shape and Size of Clamping Dies. Generally, the shape of the clamping-die surface is such that the die encompasses almost the entire workpiece surface. The required area of clamping-die surface depends on the current density needed for heating the workpiece and the pressure needed for holding it. Semicircular dies are used where the line contact provided by V-shape dies gives insufficient surface for the current to flow without burning the workpiece, or for holding the workpiece without marking it. In Example 449, a radiused lower electrode was used to conduct current to a ring-shape workpiece of rectangular cross section.

Table 3 gives the minimum lengths of clamping dies for welding rounds, tubing and other sections of various diameters or minimum dimensions; these data are for welding steels of low and medium forging strength.

Table 3. Minimum Lengths of Clamping Dies, With and Without Backup, for Flash Welding Various Diameters of Workpieces Made From Steels of Low or Medium Forging Strength (a)

Workpiece diameter, in.(a)	Length of clamping die, in. With backup	Length of clamping die, in. Without backup(b)	Workpiece diameter, in.(a)	Length of clamping die with backup, in.	Workpiece diameter, in.(a)	Length of clamping die with backup, in.
0.250, 0.312	0.375	1.00	2.00	1.25	6.00	3.25
0.375	0.375	1.50	2.50	1.75	6.50	3.50
0.500	0.375	1.75	3.00	2.00	7.00	3.75
0.750	0.500	2.00	3.50	2.25	7.50	4.00
1.000	0.750	2.50	4.00	2.50	8.00	4.25
1.50	1.000	3.00	4.50	2.75	8.50	4.50
			5.00	2.75	9.00	4.75
			5.50	3.00	9.50	5.00

(a) Diameter of rounds or tubing, or minimum dimension of other sections. (b) Backup is recommended for all workpiece diameters or minimum dimensions over 1.50 in.

Fixtures are used to support workpieces during welding and to provide orientation and alignment of workpiece surfaces that cannot be obtained by the use of clamping dies alone. Generally, fixtures have backup surfaces that absorb all or part of the upsetting force. When fixtures are used, electrodes are positioned adjacent to the joint in the usual manner for carrying current to the surfaces to be welded. The electrodes usually are attached to the clamping mechanism of the machine and are seldom part of the fixture.

The fixture shown in Fig. 4, fastened to the stationary platen of a flash welding machine, located and held a formed tube in alignment during welding. Also, the fixture provided a backup that helped resist the upsetting force. A combination backup and locator also was fastened to a bracket on the movable platen.

Horizontally sliding electrodes mounted to each platen held the abutting ends of the tubes in alignment, in addition to carrying the welding current. Since the electrodes opened in a horizontal plane, the workpieces were loaded and unloaded from the top.

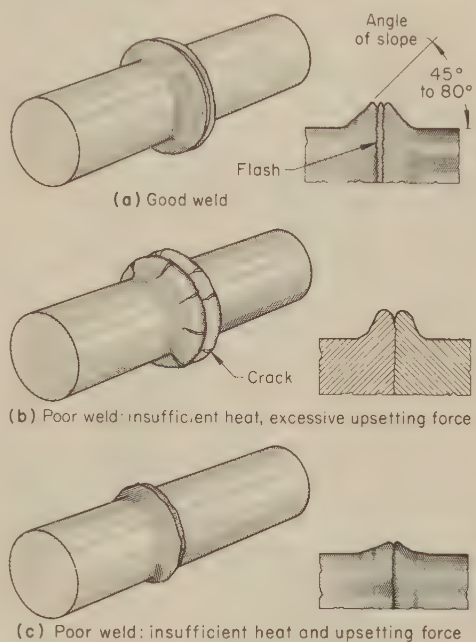


Fig. 6. Shapes of weld upset that indicate weld quality and adequacy of heat and upsetting force used during welding

Miter fixtures are used for welding miter or corner joints in steel and aluminum sash, in screen and door sections, and in structural frames such as those used for refrigerator bases.

The following example describes simultaneous flash welding of two forged steel clevises in angular alignment to the tubular midsection of a brace. In this application, light weight of workpieces, excellent reproducibility of close-tolerance dimensions, and speed were important.

Example 431. Use of a Special Fixture for Maintaining Angular Alignment in Simultaneous Welding of Two Joints (Fig. 5)

Figure 5 shows the use of a special fixture for holding two forged 1020 steel clevises in angular alignment while simultaneously flash welding them to the ends of a length of 1008 steel tubing to produce a brace. Tolerance on center-to-center dimensions of the holes in the clevises was ±0.010 in., and exact angular alignment of the holes was required.

To achieve heat balance between the clevises and the tubing, the clevises were counterbored to approximately the inside diameter of the tubing, and to a depth of about twice the amount of material lost during flashing and upsetting (see section A-A in Fig. 5).

The two joints were welded simultaneously in a synchronized double-end flash welding machine equipped with two 50-kva transformers. Each clevis was positioned on a closely fitting pin that formed part of the lower half of an electrode. Proper alignment was established by placing the tubular section of each clevis in a nest and clamping it with the upper half of the electrode. The tube was positioned by two electrodes that were mounted on the stationary platen. Vertically moving clamps held the tube in place during welding. Both movable platens were actuated by cams that controlled platen motion during flashing and upsetting, and controlled the force applied during upsetting.

Flash welding produced these parts at least cost because of the high production rate and because of the low rate of rejection. Arc welding would have increased the weight of the parts by requiring a tongue-and-socket type of joint. Friction welding would have required a complicated setup to maintain angular alignment. With pinned or riveted construction, the joints would have been weaker and the parts heavier.

Backups are used when the clamping dies cannot provide the workpiece with enough resistance to the upsetting force. This usually occurs either when the length of the workpiece adjacent to the joint is too short for effective clamping, or when the workpiece is unable to withstand the clamping force without being collapsed, scored or otherwise damaged.

A backup often consists of a steel bracket that can be bolted to the platen in various positions. Brackets can have either fixed or adjustable stops for the workpiece.

Heat for Welding

The heat necessary to make a flash weld is generated by flashing, or by a combination of preheating and flashing. Enough heat must be generated to produce a plastic zone deep enough to permit adequate upsetting.

The depth of the plastic zone and the degree of plasticity affect the slope of the upset metal. An upset with a slope between 45° and 80° (as in Fig. 6a) usually indicates that the correct amount of heat has been used and that enough upsetting has occurred. If the slope of the upset is steep and longitudinal cracks appear in the upset (see Fig. 6b), too great an upsetting force has been applied at too low a metal temperature. These cracks are similar to forging cracks, and result from the application of upsetting force before the work metal has become sufficiently plastic. If the slope is much less than 45°, as in Fig. 6(c), the heat and upsetting force have been too low.

The heat generated during flashing is concentrated at the flashing sur-

faces, behind which there is a steep decline in the temperature gradient toward the electrodes or clamping dies. In preheating, the contacting surfaces do not reach as high a temperature as in flashing, and the temperature gradient is not as steep.

Preheating

Preheating of the workpieces usually is done manually by bringing them together under relatively light pressure. Heat is generated by resistance to the flow of current in the metal exposed between the electrodes or clamping dies. Figure 2 shows that the preheat current and pressure are relatively higher than those applied during flashing. The platen is moved only enough to close the initial gap between the workpieces, and pressure is applied so that heating is accomplished by resistance instead of by flashing.

After the preheat temperature is reached, the movable workpiece is withdrawn so that flashing can start. The contact resistance of the ends of the workpieces is the major fraction of the total work-metal resistance, and therefore the metal adjacent to the contact surfaces becomes hotter than the rest of the metal between the dies. The pressure used for preheating is high enough to produce a contact area larger than that needed for sparking, but not so large that the pieces are welded together or deformed.

Preheating has two advantages: (*a*) a proper flashing action can be started more easily on heavy sections that are normally beyond the electrical capacity of a given welding machine, because the elevated temperature of the preheated contacting surfaces reduces the power demand on the machine; and (*b*) a weld can be made with less metal loss than when flashing is used alone, because preheated workpieces do not require as long a flashing action. The faster heating of the contacting surfaces results from the increased resistance of the contacting points, together with shortening of the time required for each point of contact to reach the molten state and rupture. A relatively small amount of metal is lost during preheating as a result of slight upsetting of the semiplastic metal under pressure.

Preheating is often used in order to produce a more even heat balance when the sections of the workpieces adjacent to the weld line are significantly different. Under such conditions, flashing alone may be unable to develop enough heat in the larger workpiece to produce a plastic zone of sufficient depth.

When metals having widely dissimilar elevated-temperature compressive strengths are welded, only the metal with the higher compressive strength is preheated. For example, a piece of stainless steel may have to be preheated before being welded to a piece of low-carbon steel.

Occasionally, the flashing characteristics of two metals are so different that one heats rapidly while the other heats hardly at all. When upsetting occurs, the plastic zone is large in the workpiece at the higher temperature and is very small in the cooler workpiece, and this results in poor bonding. This inequality is likely to occur when high-silicon steel is welded to low-carbon steel, and can be corrected by preheating only the low-carbon steel.

Air-hardening steels and certain other hardenable steels may require preheating before welding, and may sometimes require slow cooling in lime, powdered mica or asbestos feathers after welding. Other steels, with greater hardenability, not only require preheating, but also must be heat treated immediately after welding. For example, when 4150 steel is welded to 1040 steel in small sectional areas, a combination of preheating and postweld heat treatment produces the highest joint properties.

Table 4. Pressures Required for Upsetting Several Ferrous and Nonferrous Metals of Various Thicknesses(a)

Work metal	Thickness, in.	Pressure, psi(b)
Aluminum alloys:		
Soft	Up to 5/8	8,000 to 10,000
High-strength	...	Up to 20,000
Copper, plain	Up to 3/4	5,000 to 7,500
Heat-resisting alloys	...	Up to 35,000
Magnesium alloys	...	6,000 to 8,000
Stainless steels	Up to 2	13,000 to 25,000
Carbon and low-alloy steels:		
1020	Up to 3/8	6,000 to 10,000
	3/8 to 1	7,000 to 10,000
	1 to 2	9,000 to 11,000
	2 to 4	10,000 to 12,000
2340, 3140	Up to 1	10,000 to 12,000
4140, 6145	Up to 1 1/4	11,000 to 18,000

(a) Based on welding temperature obtained without preheating. Pressures may be as much as 50% less if preheating is used. (b) Pounds per square inch of cross-sectional area of weld.

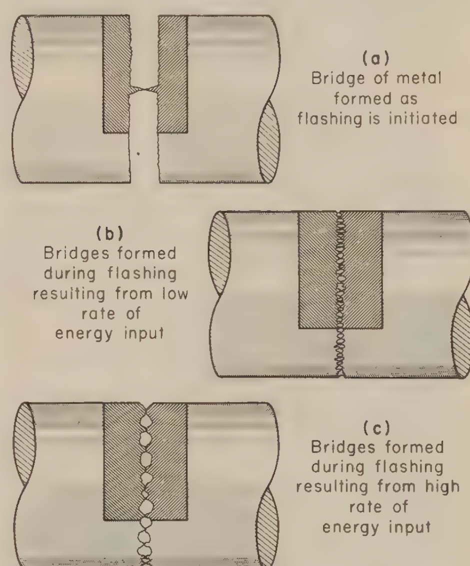


Fig. 7. Bridges of metal produced during flashing, and effects of low and high rates of energy input

Flashing

Flashing derives its name from the rapid expulsion of incandescent particles of molten metal from the bridges, or minute points of contact, between the two workpieces.

The metal in these bridges is heated to the melting point almost instantaneously, and the shape of the bridges, when in the liquid state, is believed to be determined principally by the surface tension, and is apparently characterized by a throat approximately at the center (see Fig. 7a). The incandescent particles of molten metal are thrown out with considerable velocity, which is increased by the action of the strong magnetic field generated by the flow of current. During flashing, the oxygen content of the atmosphere at the weld region is reduced because of oxygen absorption during heating of the bridges, and because of the burning of metal in air. This reduction of oxygen content produces a semiprotective atmosphere.

The primary purpose of flashing is to generate enough heat to produce a plastic zone that permits adequate upsetting. The rate of energy input must be in proper proportion to the travel of the platen or movable die so that constant flashing is maintained until the appropriate amount of metal is flashed off and the required plastic zone is obtained. The relationships of time to the flashing current and to the travel of the movable die are shown in Fig. 2.

Reduction in the rate of energy input produces a decrease in the violence of the flash expulsions, but an increase in their number and continuity, as shown by the number of small craters in Fig. 7(b); higher rates of energy input increase the size and depth of the craters left as the result of the expulsions (see Fig. 7c). Large craters such as those shown in Fig. 7(c) are undesirable because their presence makes it difficult to upset to sound metal.

The rate and duration of energy input also have an effect on the depth of the heat-affected zones. A low rate of input and a long input time result in the greatest depth of heat-affected zone, because there is more time for the heat to flow farther back into the workpiece and to cause metallurgical changes. A high rate of energy input with a short flashing time causes a large flashing gap and increases the possibility of inclusions and porosity in the weld. Inclusions and porosity can be prevented by increasing the amount of upset, but this increases the amount of metal lost in making the weld.

When a welding machine having only single voltage control is used for welding heavy, compact sections, the ease of starting the flashing action sometimes is sacrificed in order to prevent excessively high current from causing an unsatisfactory flashing action. The flashing action can be started more easily and can be accomplished more satisfactorily by using a dual voltage system. With this system, a high secondary voltage (V_1 in Fig. 2) is applied for a short time to initiate flashing. Energy input is then reduced (V_2 in Fig. 2) to provide correct flashing conditions. Dual voltage control normally is used on machines rated at 400 kva or more.

Weld Upset and Upsetting Force

Bonding takes place during the upsetting action, and some metal must be extruded from the weld zone in order to remove slag and other inclusions not expelled during flashing. The extruded

metal must extend beyond the cross-sectional boundaries of the workpiece to ensure that the maximum amounts of slag and inclusions are removed when the weld upset is removed during subsequent machining. When the weld upset is removed, there should be no evidence of the weld. Porosity near the outer surface on an etched section of the weld, or a crevice around the workpiece after the weld upset has been removed, indicates incomplete bonding because of either insufficient upsetting force or insufficient plasticity during upsetting.

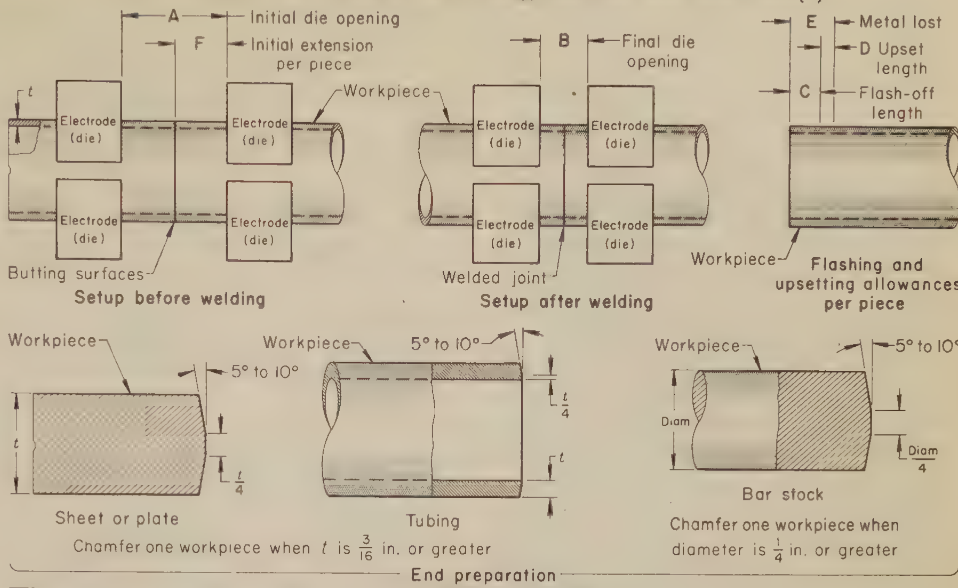
A large upset produced by an excessive upsetting force can be detrimental to weld quality, can waste metal, and indicates that most of the plastic metal has been extruded, allowing bonding to take place in metal where plasticity may not have been sufficient to ensure a good weld. Producing a large upset also is equivalent to introducing less total heat into the weld, which can result in poor weld quality. Excessive upsetting force will also bend the flow lines at the weld in a direction 90° from the flow lines in adjacent unwelded metal. Welds made under these conditions have low fatigue strength.

The quality of a flash weld is greatly affected by the upsetting force. During the upsetting action, the force should be sufficient to close all voids, to expel molten metal, slag or other impurities, and to allow complete fusion of the two workpieces.

The ability of the upsetting force to dispel molten metal, slag, and other impurities depends on several factors, including the actual force, the shape of the section, the velocity of upset, and the degree of plasticity of the metal at the time of upset. The shorter the expulsion paths of the inclusions, the easier the inclusions are to expel. The larger the ratio of perimeter to area of section in the workpiece, the more easily can slag and impurities be expelled by the upsetting force applied during flash welding.

The velocity of upset is determined by the construction of the welding machine, the manner and rate at which the upsetting force can be applied, and the amount of upsetting force exerted. For information on machine construction, see the section in this article on Equipment (page 489).

Table 5. Typical Dimensional Allowances for Flash Welding of Low-Forging-Strength and Medium-Forging-Strength Steel Tubing, Flat Stock and Solid Bars(a)



Thickness (t) of tube wall or flat stock, in.(b)	Dimensional allowance, in. (see illustration above for location and definition) A(c)	B	C	D	E	F	Flashing time, sec
Tubing or Flat Stock							
0.010	0.110	0.050	0.020	0.010	0.030	0.055	0.40
0.020	0.215	0.100	0.040	0.018	0.058	0.108	0.80
0.030	0.325	0.150	0.063	0.025	0.088	0.163	1.25
0.040	0.430	0.200	0.083	0.032	0.115	0.215	1.75
0.050	0.530	0.250	0.103	0.037	0.140	0.265	2.25
0.060	0.620	0.290	0.120	0.045	0.165	0.310	2.75
0.070	0.715	0.330	0.140	0.053	0.193	0.358	3.50
0.080	0.805	0.370	0.158	0.060	0.218	0.403	4.00
0.090	0.885	0.410	0.173	0.065	0.238	0.443	4.50
0.100	0.970	0.450	0.188	0.072	0.260	0.485	5.00
0.110	1.060	0.490	0.205	0.080	0.285	0.530	5.75
0.120	1.140	0.530	0.220	0.085	0.305	0.570	6.25
0.140	1.320	0.620	0.255	0.095	0.350	0.660	7.75
0.150	1.390	0.660	0.265	0.100	0.365	0.695	8.50
0.160	1.470	0.700	0.280	0.105	0.385	0.735	9.00
0.170	1.540	0.740	0.290	0.110	0.400	0.770	9.75
0.190	1.690	0.820	0.315	0.120	0.435	0.845	11.25
0.200	1.760	0.860	0.325	0.125	0.450	0.880	12.00
0.250	2.010	1.000	0.365	0.140	0.505	1.005	16.00
0.300	2.245	1.125	0.405	0.155	0.560	1.123	21.00
0.400	2.640	1.350	0.465	0.180	0.645	1.320	33.00
0.500	2.910	1.500	0.510	0.195	0.705	1.455	45.00
0.600	3.135	1.630	0.543	0.210	0.753	1.568	56.00
0.700	3.360	1.750	0.580	0.225	0.805	1.680	70.00
0.800	3.525	1.850	0.605	0.233	0.838	1.763	83.00
0.900	3.660	1.930	0.625	0.240	0.865	1.830	97.00
1.000	3.800	2.000	0.650	0.250	0.900	1.900	110.00
Diameter (or least sectional dimension) of bar, in.(d)	**Dimensional allowance, in. (see illustration above for location and definition) A(c)**	**B**	**C**	**D**	**E**	**F**	**Flashing time, sec**
Solid Bars (Round, Hexagonal, Square or Rectangular)(e)							
0.050	0.100	0.050	0.020	0.005	0.025	0.050	0.40
0.100	0.182	0.100	0.031	0.010	0.041	0.091	0.75
0.150	0.270	0.150	0.045	0.015	0.060	0.135	1.15
0.200	0.350	0.200	0.055	0.020	0.075	0.175	1.50
0.250	0.430	0.250	0.065	0.025	0.090	0.215	1.90
0.300	0.510	0.300	0.075	0.030	0.105	0.255	2.25
0.350	0.600	0.350	0.090	0.035	0.125	0.300	2.75
0.400	0.685	0.400	0.103	0.040	0.143	0.343	3.25
0.450	0.770	0.450	0.115	0.045	0.160	0.385	3.75
0.500	0.850	0.500	0.125	0.050	0.175	0.425	4.25
0.550	0.940	0.550	0.140	0.055	0.195	0.470	5.00
0.600	1.025	0.600	0.153	0.060	0.213	0.513	5.50
0.650	1.100	0.650	0.163	0.062	0.225	0.550	6.75
0.700	1.180	0.700	0.175	0.065	0.240	0.590	7.50
0.750	1.260	0.750	0.188	0.067	0.255	0.630	8.25
0.800	1.340	0.800	0.200	0.070	0.270	0.670	9.00
0.850	1.420	0.850	0.213	0.072	0.285	0.710	9.75
0.900	1.500	0.900	0.225	0.075	0.300	0.750	10.50
1.000	1.660	1.000	0.250	0.080	0.330	0.830	13.00
1.100	1.820	1.100	0.275	0.085	0.360	0.910	16.50
1.200	1.980	1.200	0.300	0.090	0.390	0.990	20.00
1.250	2.060	1.250	0.313	0.092	0.405	1.030	22.50
1.300	2.140	1.300	0.325	0.095	0.420	1.070	25.00
1.500	2.460	1.500	0.375	0.105	0.480	1.230	38.00
1.600	2.620	1.600	0.400	0.110	0.510	1.310	45.00
1.700	2.780	1.700	0.425	0.115	0.540	1.390	54.00
1.800	2.940	1.800	0.450	0.120	0.570	1.470	63.00
1.900	3.100	1.900	0.475	0.125	0.600	1.550	75.00
2.000	3.260	2.000	0.500	0.130	0.630	1.630	90.00

Footnotes for Table 5

(a) Data are based on welding, without preheating, of two pieces with the same welding characteristics. (b) In the views above, the boldface-letter identifications of dimensions are applicable also to flat stock — for which t would be what is shown in these views as the wall thickness of the tubing. When tubing or flat stock has t of 3/16 in. or more, ends should be chamfered as shown in "End preparation" view above. (c) When an initial gap is used between the workpieces at setup, the initial die opening (Dimension A) is increased by an equal amount.

(d) In the views above, the boldface-letter identifications of dimensions are applicable also to bar stock — for which diameter (or least sectional dimension) would be what is shown in these views as the outside diameter of the tubing. When diameter (or least sectional dimension) of bar stock is 1/4 in. or more, ends should be chamfered as shown in "End preparation" view above. (e) Values apply only when ratio of maximum to minimum cross-sectional dimension is less than 1.5.

The relation of time to the magnitude of upsetting force is shown in Fig. 2. Pressure on the platen is relatively constant during flashing, but is increased rapidly for upsetting. The upset pressure usually is constant during cool, postheat and hold times.

Normally, it can be determined whether the welding machine can provide sufficient upsetting force by observing the velocity of platen movement during upset. If the platen moves rapidly (taking only a few cycles to complete the travel during upset), enough upsetting force is available. If the platen moves slowly (taking 15 to 30 cycles to complete the travel), or if it stops before it travels through the total upset, then either the upsetting force is too low or there is insufficient depth of plastic zone in the workpiece.

The necessary amount of upsetting force is related to the temperature of the metal in the upset area, and to the compressive strength of the metal at welding temperature. Table 4 lists the pressures required for upsetting some ferrous and nonferrous alloys without preheating. With preheating, the values in Table 4 may be reduced by up to 50%.

Upsetting Current. The current is allowed to flow after the start of upsetting, to maintain the temperature and to ensure removal of foreign matter from the weld.

If the cross-sectional area to be welded is small compared to the maximum cross-sectional area that can be welded on the machine being used, the duration of current flow should be short — that is, current should stop flowing within one or two cycles after upsetting starts. If the sectional area to be welded approaches the maximum area that can be welded, duration of current flow may have to be relatively long — for example, 20 to 30 cycles after upsetting starts. The exact point of current cutoff is not critical, provided that the current is cut off some time during upsetting but before overheating takes place.

Extension of Workpieces From Dies

The amount of initial extension of the workpiece from the clamping die or electrode is determined principally by the ability of the metal to reach the correct temperature in the plastic range during preheating and flashing. Some of the heat generated by flashing is lost by radiation, and some is lost by conduction to the dies, and the initial extension must be large enough to minimize conduction loss. However, the extension must not be too large, because a large extension decreases the temperature gradient, and thus reduces the effect of the upsetting force and its ability to purge the weld through expulsion of molten metal.

Initial extensions that are larger than required can contribute to misalignment of workpieces after welding. Often, compromise must be made between welding conditions and permissible misalignment, especially in welding sheets or thin workpieces.

The size of the heat-affected zone is partly dependent on the initial and final extensions. It may be desired to harden a workpiece before welding and to retain a specified hardness after welding in a certain portion of the weld zone. By proper manipulation of the initial and final extensions of the workpiece, the desired hardness can be satisfactorily retained.

When workpieces are of the same size, shape and work metal, the initial extensions are made equal. Unequal extensions are used to assist in producing a better heat balance when equal extensions give unsatisfactory results.

Typical dimensional allowances, including lengths of initial and final extensions, for flash welding of steel tubing, flat stock and solid bars are given in Table 5.

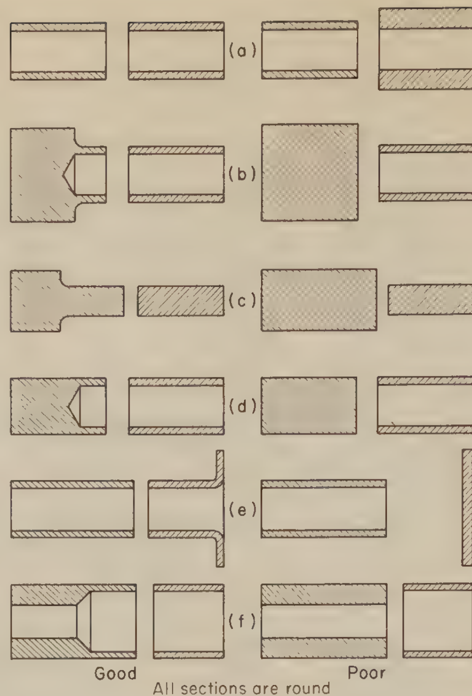


Fig. 8. Examples of good and poor joint design for obtaining heat balance between workpieces in flash welding

Workpiece Design

In designing parts to be flash welded, the following requirements and effects of the process must be considered:

1 An even heat balance should be obtained in the parts, so that the two ends to be welded attain the same degree of plasticity and depth of plastic zone during flashing.

2 The length of metal lost during flashing and upsetting must be added to the initial length of the components if the over-all length after welding is important. In designing components to be miter joined, the angle between the axis of the part and the direction of platen travel must be considered in allowing for metal lost.

3 The parts should be designed so that the reaction to the upsetting force can be resisted in a direction parallel to the line of application of force, and so that it is possible to back up and hold the parts securely during welding.

4 The parts should be designed so that they can be held in accurate alignment during upsetting. This can be done by machining locating surfaces on forgings or, as in Examples 433 and 445, by making use of the unformed ends inherent in roll forming.

5 For sound welds in workpieces to be miter joined, any nonmatching sections must be cut back so as not to interfere with flashing, and the webs must be supported or otherwise strengthened to withstand the upsetting forces (see Example 434).

6 The abutting ends should be designed so that the incandescent particles are not trapped in the weld, and on large pieces, flashing should be started at the center of the cross section of the workpiece (see Example 435).

7 In designing hollow members, consideration should be given to the possible disadvantage of upset at the inner surface. If the part must withstand fatigue loads, the stress-raising effect of the upset is important. Under corrosive conditions the metal in the upset can suffer severe attack.

Good joint design generally results in high-quality welds and consistency in production. Poor design does not necessarily mean that the parts are not weldable, but that the weld quality will be impaired and consistency in production will not be obtained.

Heat Balance Between Workpieces

Because the same welding current and upsetting force are applied to both workpieces, the thermal conditions in the two pieces must be approximately equal. To achieve heat balance, the two workpieces should have the same or nearly the same cross-sectional shape, area of contact, and contour. In general, the ratio of the areas of the two abutting surfaces should not be greater than 5 to 4.

The good designs shown in Fig. 8 are predicated on the provision of similar sections and areas in the vicinity of the weld. In the poor designs shown in Fig. 8, the heavier sections would heat more slowly, making it difficult for both pieces to reach equivalent plasticity for welding. If the thick-wall tube of the poor design in Fig. 8(a) cannot be replaced with a tube of the same wall thickness as the adjoining piece (as suggested for good design), the thick wall should be thinned for a distance from the joint by machining the outer surface of the tube. The inner surface of the thick-wall tube in Fig. 8(f) should be machined for the same reason. In Fig. 8(d), it would not be possible to obtain a weld with the strength of the base metal if the tube were welded to the solid bar, and therefore the bar should be counterbored as shown.

A degree of sectional unbalance is permissible in flash welding. When two tubes or two pieces of solid cylindrical stock are joined, the wall thicknesses of the tubes, or the diameters of the solid stock, should not differ by more than 15%. This allowance will compensate for original part tolerances or applicable tolerances on misalignment or concentricity.

In each example of good design shown in Fig. 8, the optimum length of the altered section is equal to the initial extension. The minimum length is about 125% of the metal lost during flashing and upsetting. Initial extensions for sections made of steels of low and medium forging strength are given in Table 5.

Another means of adjusting the heat balance is by special preparation of the ends of the parts to be welded. With solid bar stock, for example, a chamfered end on one of the pieces (or unequal chamfers on both pieces) will affect the heat balance by reducing the volume of metal extending beyond the clamping die. The metal with the greater heat conductivity should have the steeper chamfer.

When dissimilar metals of the same cross section are to be welded, a satisfactory heat balance can be obtained by adjustment of the initial extension. The metal having the higher thermal conductivity is extended a greater distance than is the metal with the lower thermal conductivity. This moves the weld off-center between the dies, and because of the greater length of slowly heating metal, places the weld line farther from the cooling effect of the clamping dies. Heating of the higher-conductivity workpiece is augmented also by passage of the welding current through a greater length of metal.

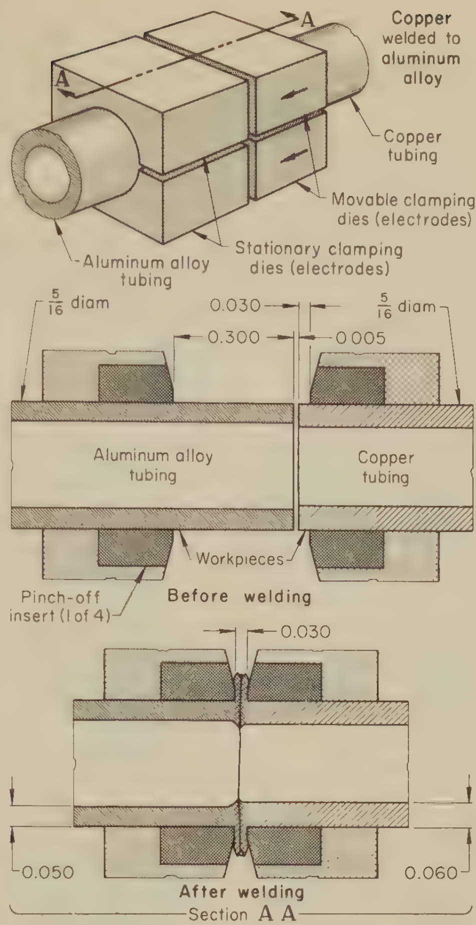
In the following example, the wide difference in the forging temperatures of the work metals was overcome by using unequal extensions of the workpieces from the clamping dies.

Example 432. Use of Unequal Extensions From Dies in Flash Welding of Aluminum Alloy Tubing to Copper Tubing (Fig. 9)

In the manufacture of refrigeration units, a short length of copper tubing was joined to the end of the aluminum alloy condenser tubing. This allowed the connection of the condenser to the remainder of the refrigeration system to be made by a copper-to-copper brazed or soldered joint.

Both tubes had outside diameters of 5/16 in.; wall thickness was 0.050 in. for the aluminum tube, and 0.060 in. for the copper tube. Heat balance would have been better if the wall of the aluminum tube had been thicker than the wall of the copper tube. The unbalance was compensated for by making the initial extension of the aluminum tube from the face of the clamping die ten times that of the copper tube, as shown in Fig. 9. Tool steel pinch-off dies were used to assist in making a better weld and to remove the weld upset from the exterior of the tubes. Flash was removed from the inside by reaming. No special end preparation of the tubing was required.

Welding conditions are given in the table that accompanies Fig. 9.



Flashing current	9000 amp at 4.5 volts
Flashing time	1 sec
Flashing travel	0.200 in.
Upsetting current	19,000 amp
Upsetting time	2 cycles (0.033 sec)
Upsetting travel	0.100 in.
Upsetting force	5000 lb
Clamping force	1000 lb
Total metal lost	0.300 in.

Fig. 9. Use of unequal extensions from dies to compensate for heat unbalance in flash welding copper tubing to aluminum alloy tubing. Pinch-off die inserts were used to remove the weld upset at the end of the upsetting stroke. (Example 432)

As shown in Fig. 10(a), several flash welds can be made simultaneously between two workpieces of the same thickness, even if the weld areas are different. The ratio of the areas should not be greater than 5 to 1. Welding of unequal areas is possible because initial die openings and flashing times used in welding tubing and flat stock (see Table 5) are based on stock thickness. However, simultaneous flash welds between solid round sections (see Fig. 10b) must have equal areas to be of uniformly good quality, because initial die openings and flashing times are different for each workpiece diameter (see Table 5).

Compensation for Metal Loss

In flash welding, some work metal is lost in making the weld. The amount of metal lost varies with the diameter, or least sectional dimension, of solid bars, the thickness of flat stock, or the wall thickness of tubing. To allow for metal lost, each component must be made longer than its final length in the weldment. In addition, the parts must overhang the clamping dies a certain distance, which is also proportional to the least sectional dimension of solid stock or to the wall thickness of tubing. (See the section on Extension of Workpieces From Dies, page 494.) Table 5 gives lengths of metal lost and die spacings for various sizes of steel tubing, flat stock, and solid bars. These values may vary, depending on the specific welding conditions.

In miter joining, the components are set at an angle to the platen, and so the amount by which the workpiece length is increased to compensate for metal that will be lost during flashing and upsetting also must allow for the miter angle. Because metal lost usually is measured parallel to platen travel, the length of the workpiece, measured along its centerline or edge, must be increased by a value equal to the amount of platen travel divided by the sine of the angle between the centerline or edge of the workpiece and the miter-cut end. If there is a gap between the ends of the workpieces after they have been secured by the clamping dies, the gap dimension must be deducted from the platen travel for this calculation.

Parallel Resistance to Upsetting Forces

Parts should be designed so that the reaction to the upsetting force can be resisted parallel to the direction in which it is applied, and so that the parts can be securely backed up and held during upsetting. Suitable backup tooling usually is needed for welding various shapes of forgings and bent tubing, and backups are also used as locators to facilitate loading and to obtain proper alignment of workpieces, as shown in Fig. 4.

There should be sufficient clamping area on the workpiece to permit the necessary clamping force to be applied without distorting the workpiece. Also, the shape of each workpiece should be such that alignment of the workpieces is not affected by the upsetting force.

Flash welding of rings is an application in which the plane of the workpiece that extends between the clamping dies is not always parallel to the plane of the upsetting force. The closed side of the ring also offers mechanical resistance to the normal upsetting force. This resistance can be used to advantage by forming the ring so that the ends are tightly together, or slightly overlapping. In this way, the forces for forging and bending the ring that are exerted through the clamping dies can be reduced. When rings are welded, the metal in the closed side is heated and expands, which causes some slippage in the die. Therefore, the ring should not be

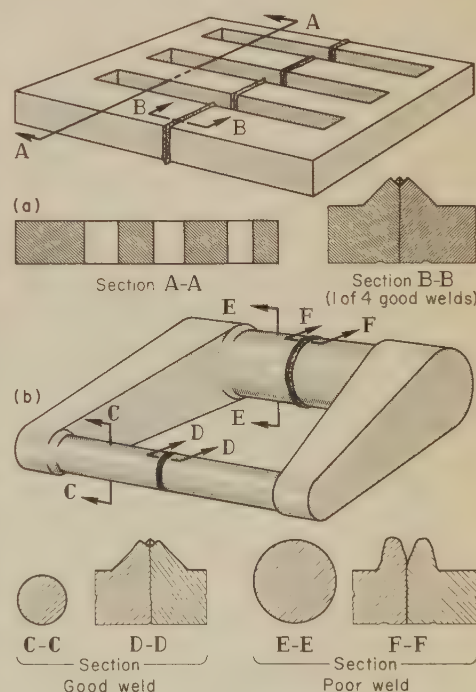


Fig. 10. Quality of simultaneous multiple flash welds of unequal cross-sectional areas. See text for discussion.

clamped completely around its circumference. Sometimes, however, when the material is burned away at least as rapidly as the ring expands, it is possible to use a circumferential clamping mechanism. Another effect of heating the closed side is alteration of the metallurgical properties of the ring after welding.

Care should be taken to avoid interference between the workpiece and the clamping mechanism; this can be difficult when small-diameter rings are being welded. Successful welding of rings depends on the ability of the clamping mechanism to hold the ends in place without slippage during the forging action.

Examples 433 and 445 describe applications in which advantage was taken of the unformed ends of roll formed bands in applying parallel forces during welding.

Not all sizes of rings or cylinders can be welded, because the closed side of the ring shunts the welding current, thus reducing the power that crosses the flashing gap. If the circumference of the ring is less than 25 times the thickness of the section, the shunting effect is so great that it is difficult to maintain flashing, and the closed side of the ring may melt through.

Alignment of Workpieces

Workpieces must be properly aligned to obtain good welds. Misalignment results in poor flashing and incomplete upset. Figure 11 illustrates the effect of good and poor alignment.

Maintenance of alignment and concentricity during flashing and upsetting is difficult in welding thin-wall tubing or workpieces with relatively thin sections. The edges of sheets must be held by the clamping dies so that ripples resulting from previous operations do not cause misalignment. If the edges are bent and do not mate, the sheets will overlap each other, instead of upsetting and welding together. Overlap generally is confined to small local areas along the welded edge, and in these areas poor fusion occurs. Reducing the thickness of the welded sheet by rolling can cause weld failure.

The example that follows describes flash welding of a ring that was roll formed from a stainless steel band. Alignment was maintained by leaving two unformed (flat) ends at the joint to be welded and by using clamping dies that had the same radius as the roll-formed ring.

Example 433. Flash Welding of a 0.078-In.-Thick Stainless Steel Ring (Fig. 12)

The ring shown in Fig. 12 was fabricated from 17-7 PH stainless steel coiled strip 1²¹⁄₃₂ in. wide by 0.078 ± 0.002 in. thick. The strip, annealed and pickled and with a 2B finish, was uncoiled, flattened, pierced with 16 holes ¼ in. square, and cut to a length of 18.08 in. Each length was then roll formed into a ring with a ³⁄₁₆-in.-long flat on each end. These flats helped to keep the ends in alignment during flashing and upsetting. The ends of the band were trimmed to ensure uniform flashing at the start. Then the band was manually loaded and clamped in the flash welding electrodes (see Fig. 12). A clamping force of 4600 lb was exerted on an area of about 1½ sq in.

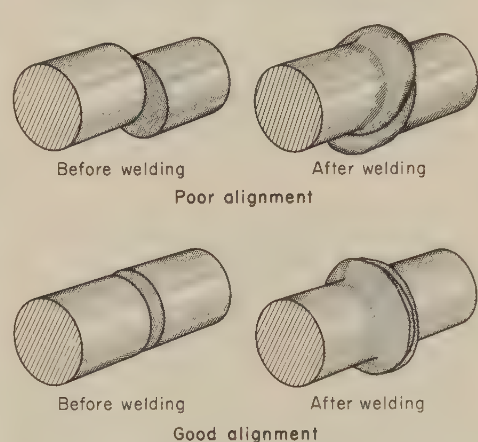


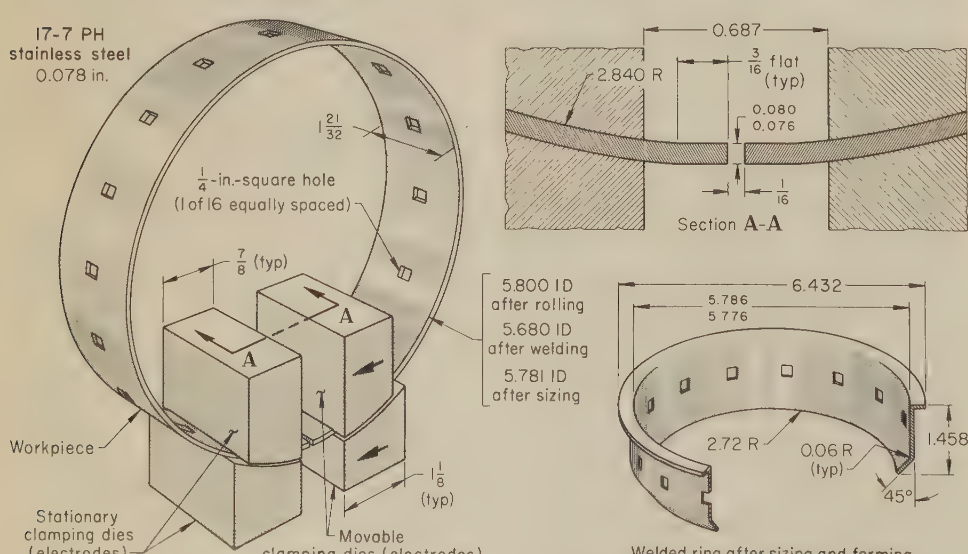
Fig. 11. Effects of alignment of workpieces on welded joint and weld upset

The clamping dies were made of RWMA class 3 electrode material. Power leads from the 50-kva (50% duty cycle) transformer were attached directly to the electrodes. The primary voltage input to the transformer was 220 volts and the secondary output voltage was 4.1 to 6.9 volts in eight steps. The platen speed and travel were controlled by a cam mechanism driven by a synchronous motor. The operation was semiautomatic in that the workpiece was loaded and clamped manually and then the welding cycle was started by the operator. After the automatic flashing and welding cycle was completed, the ring was manually unclamped and transferred to a machine for scarfing the weld upset.

Production rate was one ring in 24 sec, or 150 rings per hour. Flashing and upsetting required 2.58 sec.

The flash welded rings were given an intermediate anneal at 1400 F for 1½ hr, and then were cooled to 60 F within 1 hr. The annealed rings were stretched to an inside diameter of 5.776/5.786 in., and then were formed with a 90° stretch flange and a 45° shrink flange, which proof tested the welded joint. Tension testing of the flash welded joint showed that the metal in the weld zone had a strength equal to that of the base metal.

The rings were given a final heat treatment at 1050 F for 1½ hr, and then were air cooled. This produced a hardness of Rockwell C 40 to 50. Hardness tests indicated that the metal in the weld zone responded to the heat treatment in the same manner as did the base metal. (Costs for flash welding and gas tungsten-arc welding this ring in lots of 40 pieces are compared in Example 450.)



Welding Dimensions and Conditions

Initial die opening	0.687 in.	Total metal lost	0.474 in.
Initial extension per piece	0.312 in.	Flashing current	10,000 amp
Initial gap at joint	0.063 in.	Flashing time	2.50 sec
Final die opening	0.150 in.	Upsetting current	27,000 amp
Flash-off length, total	0.314 in.	Upsetting time	0.08 sec
Upset length, total	0.160 in.	Upsetting velocity	2 in. per sec

Fig. 12. Setup and joint detail for flash welding of a ring made from a roll formed band, prior to sizing and forming. Flats at joint (see section A-A) and use of conforming-radius electrodes kept ends aligned during welding. (Example 433)

Some combinations of joint length and stock thickness are difficult to weld and some are impossible to weld. Table 6 gives the relationships of joint length (sheet width) to sheet thickness that have proved successful in a large number of production jobs.

Relationships of tube diameter to wall thickness that have been successfully welded are listed in Table 7. When the ratio of tube diameter to wall thickness is too large, the clamping dies may deform the tube enough to cause mismatch of the tube ends, producing an incomplete or defective weld in that area.

Diametral tolerances are most critical when extremely thin-wall tubes are being welded, because the ends of out-of-tolerance tubes will not mate accurately at all points around the circumferences of the tubes. A difference in tube diameters also can cause a telescoping action, which reduces the effectiveness of the upsetting action, and thus reduces the properties and quality of the weld.

Standard steel tubing generally is oversize, and therefore the dimensions and tolerances of pieces to be welded should be based on the actual rather than the nominal dimensions. Military specifications require that the ratio of diameter to wall thickness not exceed 30 to 1. Although good welds can sometimes be obtained when this ratio is exceeded, selective assembly or sizing of the tubes may be necessary.

Miter Joints

Flash welded miter joints inherently have less-than-optimum weld quality, because the line of application of upsetting force is not parallel to the centerline of the workpiece, and there are variations in the resistance to the upsetting force in the horizontal plane of the abutting surfaces. However, miter joints have been satisfactorily flash welded in bar stock, flat rectangular sections, solid and hollow extruded sections, contour roll formed sections, and structural sections. Solid, compact sections such as bar stock must be joined at an included angle of not less than 150°, as shown in Fig. 13(a). Poor bonding occurs at the outer corner as a result of the absence of backup material.

Satisfactory 90° welds have been made in thin rectangular sections, and in similar extruded or roll formed sections, where the width of the joint, w, is greater than 20 times the stock thickness, t (see Fig. 13b). Slippage of the workpiece during upsetting is a normal consequence unless the clamping dies are properly designed and unless workpieces are carefully placed in the dies and aligned.

It is impossible to obtain 100% bonding throughout all parts of a flash welded miter joint, because some portions of the weld area are not backed up with cold metal to give support during upset. The lack of backup metal prevents the development of adequate forging pressure, and results in poor bonding at outside corners (see details A and B in Fig. 13). Thus, miter joints are inadvisable for assemblies to be subjected to high stresses in tension or torsion. To safeguard against stress concentration at light and medium loads, the poorly bonded metal at the outside corner of the joint should be removed, as indicated by the trim line in detail B in Fig. 13. When thin rectangular sections are joined at an angle, little heat flows beyond the welding surfaces, because welding time is short; in thin sections, however, a deep zone of plasticity is unnecessary.

Accurate cutting of the ends of workpieces for miter joints is not essential. Slight inaccuracies in straightness or angularity of the abutting ends cause initial point contact at the start of flashing, and help to initiate a smooth flashing action. The values given in Table 5 can be used as a guide in determining dimensional allowances for bar stock, extrusions, tubing and sheet stock.

Extrusions having different cross-sectional shapes, such as the header, the jambs and the sill of a window frame, frequently must be flash welded together in a miter joint. When the ends are prepared for welding, the portions that are not to be welded, or any nonmatching portions of the extrusions, must be cut back for a distance equal to or greater than the length of metal lost during flashing and upsetting, as shown in Example 434. Otherwise, flashing will occur between these portions and other parts of the workpieces or the clamping dies. When properly trimmed, the ends of the extrusions will terminate in the miter exactly at the weld line.

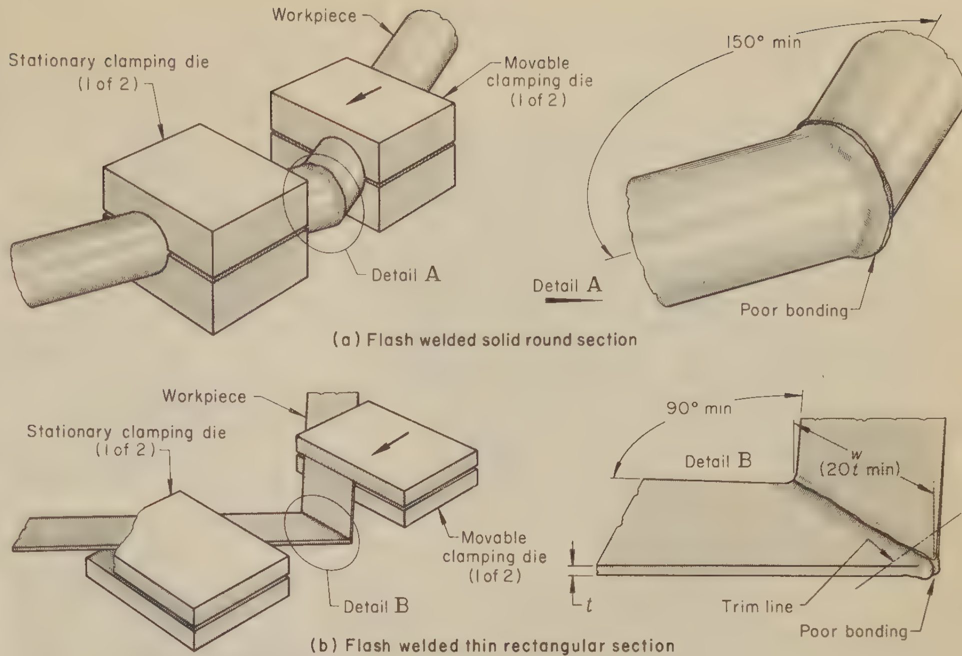


Fig. 13. Setups and dimensional relations for flash welding of miter joints in round and thin rectangular sections. Poor bonding at outer corners results from lack of backup metal.

Table 6. Lengths of Joints Commonly Flash Welded in Various Thicknesses of Flat Sheet

Sheet thickness, in.	Joint length, in.	Sheet thickness, in.	Joint length, in.
0.010	1	0.060	25
0.020	5	0.080	35
0.030	10	0.100	45
0.040	15	0.125	57
0.050	20	0.187	88

Length of joints in stock thicknesses of 0.050 in. and greater can be up to 100 in., depending on material extension, platen travel, die alignment and clamping.

Table 7. Maximum Flash-Weldable Diameters of Tubing of Various Wall Thicknesses

Wall thickness, in.	Max diameter, in.	Wall thickness, in.	Max diameter, in.
0.020	½	0.125	4
0.030	¾	0.187	6
0.050	1¼	0.250	9
0.062	1½	0.375	15
0.080	2	0.500	20
0.100	3		

Adequate support and clamping are important in miter-joint welding of extrusions and roll formed sections that incorporate thin webs, because the plane of the thin web is not in the plane of the upsetting force. Where the length of the thin vertical web is greater than twice the web thickness, the upsetting force is more likely to displace metal from the joint rather than to upset the metal correctly, and a poor weld may result. In applications where a liquid-tight joint is not required between sections having long, thin webs, the webs can be cut back so that, at the end of flashing and upsetting, the webs are in intimate contact but are not welded. Where a liquid-tight joint is required, the webs can be formed so that they are in the same plane as the upsetting action.

In the application described in the following example, after the miter cut was made in the window-frame extrusions to be welded, the end of the web was formed so that it would be parallel to the upsetting force. Also, portions of the extrusions not to be welded were trimmed away so that they would not interfere with other parts of the weldment or the welding operation.

Example 434. Miter-Joint Welding of Window-Frame Extrusions, in Which Weld Strength Was Increased by Preforming Abutting Edges of Thin Webs (Fig. 14)

Aluminum alloy 6063-T5 extrusions were used in making a window frame in which the corners were mitered and joined by flash welding as shown in Fig. 14. Watertight corners were required, and so the thin vertical web sections of the extrusions had to be made part of the welded joints. To provide the strength in the web needed to resist the upsetting force, a V-shape embossment was formed in the end of each web before welding, as shown in Fig. 14; thus, a portion of the web was in line with the platen travel during the later part of flashing and during upsetting. The clamping arrangement shown at the lower right in Fig. 14 was designed to provide adequate support and accurate alignment of the thin web sections.

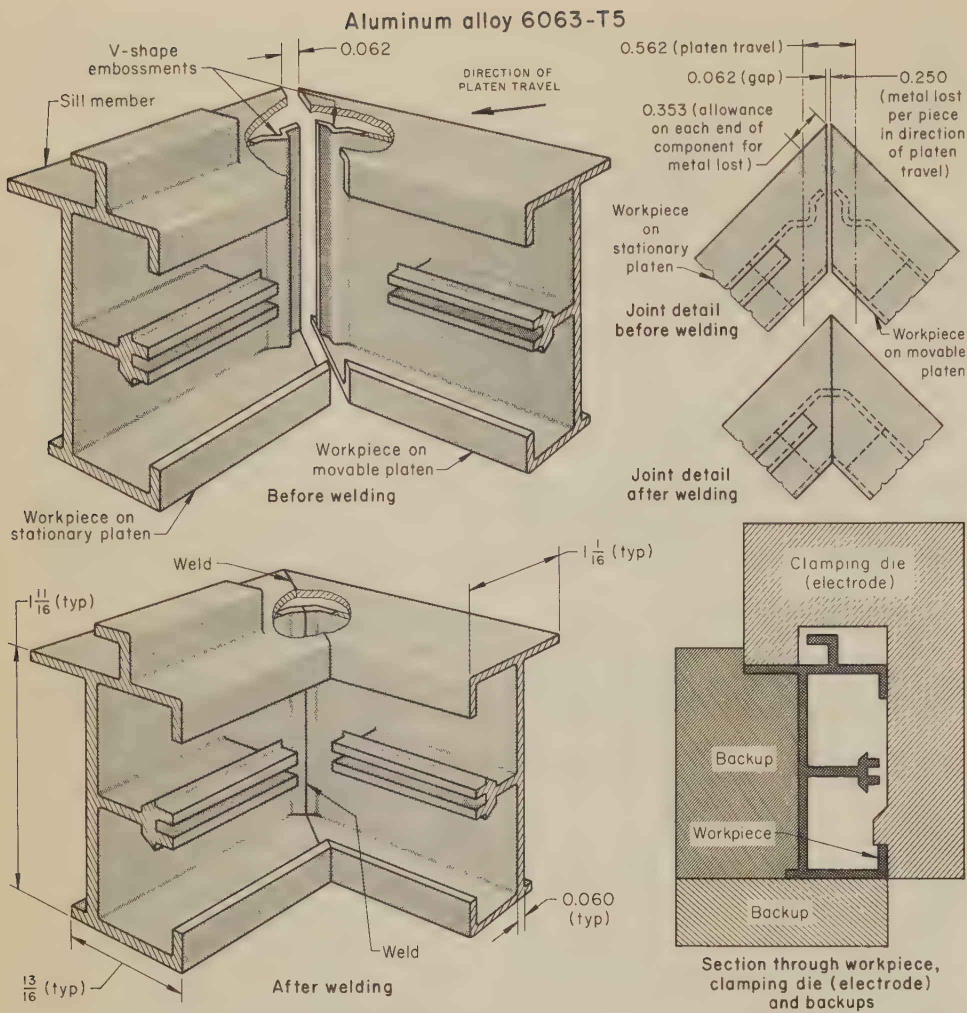
The right-angle projection along the surface of the $1\frac{1}{16}$-in.-wide flange on the sill member was cut back to prevent interference with flashing and upsetting. The inward-pointing projections on the edges of the flanges were short enough to withstand the upsetting force and to provide adequate weld strength, and thus were not cut back. The center bars of the E-shape members were not to be welded, and so were cut back on the ends of each piece.

Production was over 200 frame assemblies (800 welds) per day. The weld area was 0.334 sq in. A 150-kva flash welding machine was used in which platen travel during flashing and upsetting was actuated by a motor-driven cam.

Other welding conditions are given in the table that accompanies Fig. 14.

Expulsion of Flash

Heating of workpieces during flash welding is accompanied by the rapid expulsion of incandescent particles of molten metal. These particles contain slag and oxide that constitute defects



Welding Dimensions(a)		Welding Conditions	
Initial die opening	0.578 in.(b)	Flashing current	13,600 amp at 6.3 volts
Initial extension per piece	0.258 in.	Flashing time	1.8 sec
Final die opening	0.016 in.	Upsetting current	None (power off)
Metal lost per piece	0.250 in.(c)	Upsetting time	3 cycles (0.05 sec)
Flash-off length, total	0.250 in.	Upsetting force	24,000 lb
Upset length, total	0.250 in.	Clamping force	5000 lb

(a) In direction of platen travel. (b) Includes 0.062-in. initial gap between parts at joint. (c) Because of the miter angle, allowance at each end was 0.353 in. instead of 0.250 in.

Fig. 14. Miter joint between window-frame extrusions before and after flash welding, and details of workholding arrangement. V-shape embossments at meeting edges of the thin web sections aided in the production of strong, watertight welds. (Example 434)

if trapped in the weld. Risk of entrapment is lessened when the particles are expelled along the shortest path. On round-section workpieces, the shortest paths lie on radial lines starting at the center of the weld area.

In designing the abutting ends of workpieces, especially of large-diameter workpieces, the mating surfaces can be chamfered as shown in the illustration that accompanies Table 5. This causes the flashing and heating to start at the center of the workpiece and to move progressively toward the outer edges. The chamfered surfaces also help to expel the flash particles during initial flashing.

In the example that follows, the abutting ends of large-diameter workpieces were machined to a point instead of a flat surface. This ensured that flashing would start at the center of the weld area and that the incandescent particles would be expelled along the shortest paths.

Example 435. Welding of Forged Crankshaft Sections on Which Ends Had Been Machined to a Point To Aid in Expulsion of Flash (Fig. 15)

In the production of a 14-ft-long crankshaft for an eight-cylinder engine, two 7-ft-long forged sections of 5046 steel were flash welded together at an 8-in.-diam main bearing. The two surfaces to be welded were machined to a conical shape with a 4° slope from center, as shown in Fig. 15. This caused flashing and heating to start at the center of the shaft and allowed space for the sparks (iron and oxide) to be expelled from the weld area. The opposite side of the cheek on each half of the main bearing was machined to accommodate backups that were mounted on each platen to resist the flashing and upsetting forces. During welding, a fixture mounted on each platen positioned and held each forging, and split-type water-cooled copper electrodes conducted current to the workpieces.

Each half of the crankshaft was placed and clamped in its respective fixture. The electrodes were brought in contact with the bearing surfaces and hydraulically clamped. The two halves of the crankshaft were brought into initial contact by manually actuating the movable platen. Flashing was continued by manually feeding the platen for about half the welding cycle, after which an automatically controlled hydraulic feed was used. When the interfaces were slightly below the melting temperature, upsetting pressure was suddenly applied. The welding current was automatically turned off shortly after the start of upset, but the upsetting pressure was maintained for a short period to permit the workpiece to cool below the solidification temperature, and to maintain alignment during cooling.

The weld upset was removed with a scarfing tool and the weld area was annealed by induction heating. The main-bearing surface was finished to diameter by grinding. The forgings had been quenched and tempered to 270 to 300 Bhn before they were welded.

The welding machine had an input rating of 1750 kva. The output rating of the secondary was 2700 amp at 16 volts during manual feed, and 3000 amp at 12 volts during automatic feed. Platen force during manual feed was 36 tons, and during automatic feed, 94 tons. Two hydraulic cylinders were used — one for manual feed, and the other for automatic feed.

Total welding time was 6 min; upsetting pressure was held for an additional 3 min. Welds were inspected ultrasonically.

Typical Welding Schedules

Flash welding schedules are based primarily on the diameter of bar stock, on the thickness of sheet or plate, or on the wall thickness of tubing, and not on the entire cross-sectional area of the workpiece. Because of the distribution of electrical energy, it is easier to weld a plate 1 in. by 12 in. than a bar 3 in. by 4 in., even though both have the same cross-sectional area. The maximum cross section that can be successfully welded depends primarily on the strength of the work metal at elevated temperature.

Table 8 gives welding schedules for plates, bars and tubes made of various metals and alloys.

The Heat-Affected Zone

In a flash welded part, there are significant metallurgical differences between the highly heated structure at the center of the weld and the unaffected base metal. These differences occur because there is a large temperature gradient in the work metal between the inner edges of the clamping dies or electrodes. The greatest heat is generated at the faces of the weld because of the flashing action, while at the inner edge of the electrodes the metal is essentially at room temperature. The heat-affected zone is the region on each side of the bond line that has been heated during welding to temperatures above or within the transformation-temperature range. The portions of the work metal other than the weld and the heat-affected zone remain relatively cool and conduct heat away from the weld. Consequently, the weld cools at a much higher rate than would be obtained during simple air cooling and, in steel, hardening results, particularly when the welded section is small. There is not only a marked change in microstructure across the weld, but also a variation in hardness — to a small ex-

Table 8. Typical Flash Welding Schedules for Plates, Bars and Tubes of Various Metals

Work metal, and section size in inches	Die opening, in. Initial	Die opening, in. Final	Flash-off length, in.	Upset length, in.	Total metal lost, in.	Flashing time, sec	Upsetting time, cycles	Heat setting, volts
Plates								
1020 steel, 0.25 by 16.75	2.00	0.75	0.75	0.50	1.25	12	8	6.02
Alloy steel(a), 1.165 by 9.95	3.00	1.25	1.00	0.75	1.75	25	50	8.17
Inconel X-750, 0.5 by 6.5	3.44	1.25	0.81	1.38	2.19	18	40	5.8
Inconel X-750, 1.5 by 6.0	4.44	1.75	1.06	1.63	2.69	25	75	8.17
Solid Bars								
Low-carbon steel welded to M10 tool steel, 0.875 diam	2.25(b)	1.50	...	...	0.50	7(c)	60	6.28 max
8620 steel, 0.405 by 0.505(d)	0.94	0.44	0.31	0.19	0.50	3.5	0.5 sec	4.5
8620 steel, 2.56 diam	3.75	2.25	1.10	0.40	1.50	57	40	7.2
8640 steel welded to HS-31 alloy, 1.5 diam	3.41(e)	2.31	...	...	0.88	25	...	45,000 amp
Tubes								
1008 steel welded to 1010, 1.125 OD by 0.090 wall	0.75	0.25	...	...	0.50	4	...	(f)
AMS 6324 steel (8740 mod), 4.94 OD by 0.52 wall(g)	3.25	2.03	0.86	0.36	1.22	32	40	6.8
AMS 6427 steel(h), 1.94 OD by 0.22 wall	1.76	1.00	0.55	0.21	0.76	20	...	4.8
AMS 6427 steel(h), 8.75 OD by 0.78 wall(g)	5.12	2.02	2.57	0.53	3.10	120	40	10.9
Titanium alloy Ti-6Al-4V, 3.5 OD by 0.5 wall(g)	2.60	1.50	0.55	0.55	1.10	30	9	5.2

(a) 0.20 C, 1.0 Cr, 1.0 Mo, 0.1 V, 0.75 Si, 0.5 Mn. (b) Workpiece extensions: low-carbon steel, 1.62 in.; M10, 0.38 in.; 0.25-in. gap. (c) Includes 3-sec preheat. (d) Ring-gear blank. (e) Workpiece extensions: 8640, 1.59 in.; HS-31, 1.82 in. (f) No. 5 tap of eight taps on a 50-kva welding transformer. (g) Welds were made in protective atmospheres: 1000-Btu city gas for the AMS 6324 and AMS 6427 steels, argon for the Ti-6Al-4V titanium alloy. (h) 0.28 to 0.33 C, 1.8 Ni, 0.85 Cr, 0.40 Mo, 0.07 V.

tent in steels of low hardenability, and to a greater extent in steels of high hardenability.

Solution quenched, annealed or other types of structures appear in alloys not subject to martensitic hardening. In all alloys, the grain size at the weld is large and becomes smaller as the distance from the bond line increases.

In some alloys, the desirable characteristics of flash welds include a narrow hardened or heat-affected zone, and strength and ductility as nearly equal to those of the base metal as possible. A weld with these characteristics can undergo subsequent cold forming or cold reduction to the same degree as can the base metal. Sometimes, weld quality can be improved by welding in an atmosphere other than air. Results of flash welding 4335 steel in six different atmospheres are given in Example 442.

Hardness of Welds

A hardness survey across a flash weld in cold rolled low-carbon steel shows little change in hardness. Therefore, heat treatment is unnecessary for obtaining uniform hardness. When a hardenable steel is flash welded, considerable hardness differentials are produced across the heat-affected zone. If uniform hardness is desired, heat treatment after welding is necessary.

Flash welds in cold rolled low-carbon steel have a coarse structure near the weld and contain some martensite. During flashing, considerable grain growth occurs in the metal at the joint because the temperature is near or above the melting point, which is far above the transformation-temperature range. (Theoretically, all the metal that is melted at the bond line is extruded into the weld upset.) Proceeding from the bond line along the workpiece, the temperature decreases, and any martensite present becomes increasingly finer in appearance. Near the outer edge of the heat-affected zone, where the metal has been heated to a temperature between the lower and upper transformation temperatures, only partial transformation occurs, which results in softening of the steel.

Variations in hardness across the heat-affected zone in cold rolled low-carbon steel are illustrated in Fig. 16(a). The hardness of the metal in the heat-affected zone is lower than that of the unheated base metal because heating has removed the work hardening resulting from cold rolling. The bond line and points near the outer edges of the heat-affected zone are slightly softer than the rest of the heated metal. During a tension test, fracture can be expected to occur near the outer edges of the heat-affected zone because of the slight softening.

After flash welding of hot rolled steel, the metal in the heat-affected zone is harder than the base metal as a result of heat treatment during welding. Therefore, in a tension test of a flash weld in hot rolled steel, fracture usually occurs in the base metal.

A flash weld in an alloy steel containing 0.25 to 0.28 C, 0.60 to 0.80 Cr, 0.80 to 1.00 Ni, and 0.50 to 0.60 Mo has a fully martensitic structure, because of the high hardenability of the steel. The martensite becomes more finely divided as the distance from the bond line increases, because of the decreasing temperature gradient. In a region near the edge of the heat-affected zone where the metal temperature approaches the lower transformation temperature, the original base metal is only partly transformed; after cooling, the microstructure is ferrite and fine-grain martensite.

Variations in hardness across a weld in a Cr-Ni-Mo alloy steel of the composition noted above are illustrated in Fig. 16(b). From the original hardness

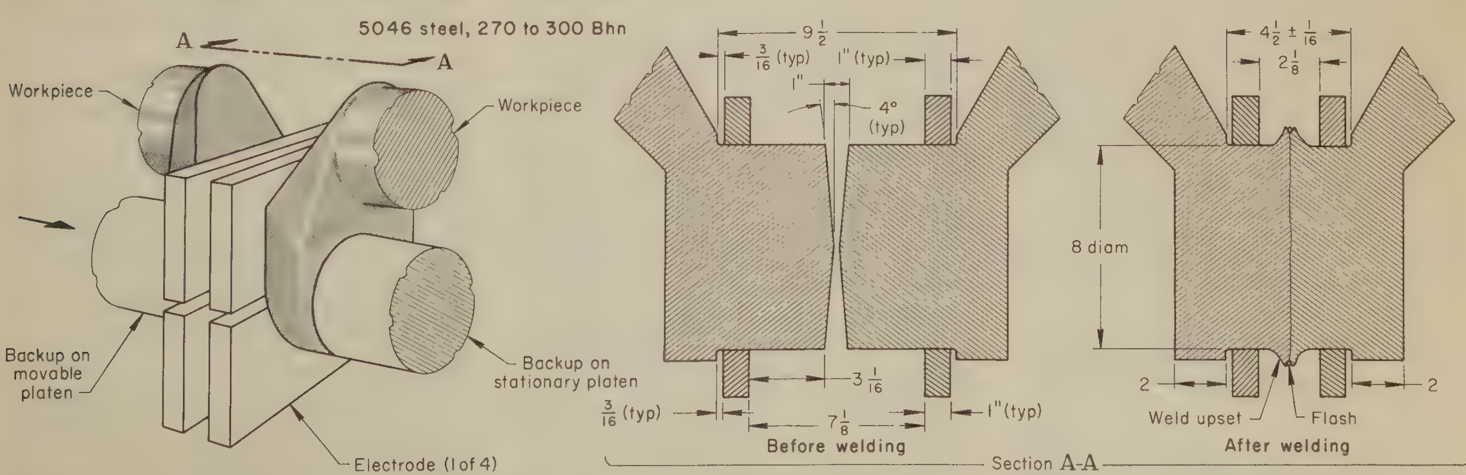


Fig. 15. Setup and joint details for flash welding of two halves of a 14-ft-long crankshaft at an 8-in.-diam main bearing. Expulsion of flash from the thick sections was aided by a 4° conical relief machined on each surface to be welded. Total metal lost, exclusive of the tapered ends, was 4 in. (Example 435)

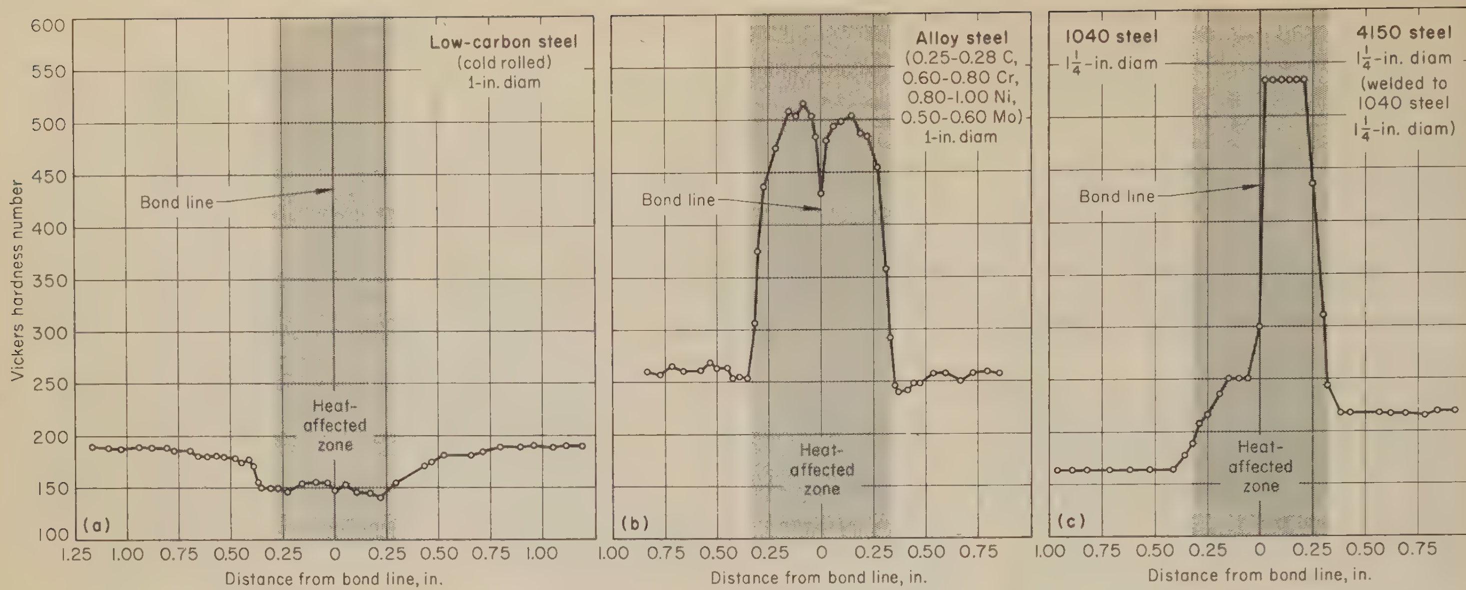


Fig. 16. Variation in hardness across the heat-affected zone and into the base metal for flash welded joints in: (a) *cold rolled low-carbon steel;* (b) *a Cr-Ni-Mo alloy steel; and* (c) *1040 steel welded to 4150 steel*

of the base metal (about 260 Vhn), the hardness rises sharply at the edge of the heat-affected zone and is higher than 500 Vhn (Rockwell C 48 to 50) near the bond line. The dip in hardness at the bond line is probably caused by decarburization. During welding, the regions on either side of the bond line are heated to a temperature high enough to cause full hardening during cooling, and the hardness decreases with the distance from the bond line.

The lowest hardness in the welded joint was just beyond the heat-affected zone where a temperature slightly higher than the tempering temperature (1200 F) of the original base metal had been reached. Had the original tempering temperature been lower, and the hardness of the metal consequently higher, the dip in hardness would have been more noticeable.

A hardness plot taken across the center of 1¼-in.-diam bars of 4150 steel and 1040 steel that were flash welded together is shown in Fig. 16(c). Although similar in carbon content, the two steels differ greatly in hardness within the heat-affected zone, because of the greater hardenability of the 4150 steel. During welding, the 4150 steel was hardened to such an extent that it cracked at the outer edge of the heat-affected zone during cooling. Both of the bars were fully annealed before welding; therefore, there was no dip in hardness between the heat-affected zone and the unheated base metal.

The group of four examples that follows demonstrates the variation in hardness in the heat-affected zones in flash welds between two commonly used alloy steels.

Examples 436 to 439. Variations in Hardness Across the Heat-Affected Zones in Flash Welded Alloy Steel Rings of Four Sizes (Fig. 17)

Figure 17(a) to (d) shows the variations in hardness across the heat-affected zones of four flash welds in alloy steel rings of different inside diameters and cross-sectional areas. All four rings were flash welded in a welding machine with an input rating of 750 kva. The maximum short-circuit output rating of the secondary was 240,000 amp at the highest transformer tap setting. Clamping force and platen movement were hydraulically actuated. The maximum clamping force was 620,000 lb with a hydraulic pressure of 2000 psi. Maximum force on the platen (flashing and upsetting) was 208,000 lb at 1000 psi.

The lower clamping dies, which were attached to the platen and carried the current, were made of RWMA class 3 electrode material. The upper dies were made of an oil-hardening tool steel and were hardened to Rockwell C 42 to 45. Both sets of dies were shaped to the contour of the specific ring being welded, and the upper dies were serrated to resist slippage during upsetting.

Conditions for welding the four different rings are given in the table that accompanies Fig. 17.

Example 436 (Fig. 17a). A ring with an inside diameter of $18\frac{15}{16}$ in. was made from 4130 steel bar stock by roll forming and flash welding. The bar was 1.06 in. square, with a cross-sectional area of 1.12 sq in. After being welded, the ring was machined to a cam contour on one face and was used to apply a brake in the transmission of a military tank. Production rate was 40 rings per hour.

A plot of the hardness across the heat-affected zone of the as-welded ring is shown in Fig. 17(a). Note the sharp drop in hardness at the bond line.

After being welded, the ring was annealed to condition the heat-affected zone for a subsequent sizing operation. The annealing treatment consisted of holding at 1750 F for 1 hr, furnace cooling to 900 F and then air cooling; the hardness after this treatment was 249 Bhn max. Then the base metal and the metal in the heat-affected zone were proof tested by 1% minimum elongation of a section between two gage points. This operation also expanded the ring to size. Before final machining, the ring was quenched and tempered to Rockwell C 26 to 32.

Example 437 (Fig. 17b). A tank-transmission steering-clutch ring $10\frac{11}{16}$ in. in inside diameter was made from 4130 steel bar stock 2⅛ by 5 in. by forming with a compression die in a 500-ton horizontal press and then flash welding. The cross-sectional area of the welded joint was 10.6 sq in. Production rate was 15 rings per hour.

The as-welded hardness of the metal in the heat-affected zone is plotted in Fig. 17(b). Note that the metal at the bond line was only about 2 Rockwell C points softer than the immediately adjacent metal in the heat-affected zone.

After being flash welded, the ring was heated to 1200 F, compression formed for rounding, and expanded (2% max) to size. Then the ring was welded into the tank-transmission assembly, and the entire assembly was quenched and tempered to Rockwell C 26 to 32.

Example 438 (Fig. 17c). A $7\frac{7}{16}$-in.-ID ring (a blank for an internal-reversing ring gear for a transmission planetary-gear system) was made from 4140 steel bar stock 1⅛ by $2\frac{1}{16}$ in. by roll forming and flash welding. The cross-sectional area of the welded joint was 2.3 sq in. Production rate was 30 rings per hour.

The as-welded hardness of the metal across the heat-affected zone is shown in Fig. 17(c). The hardness of the metal at the bond line averaged about 6 Rockwell C points less than that of the immediately adjoining metal.

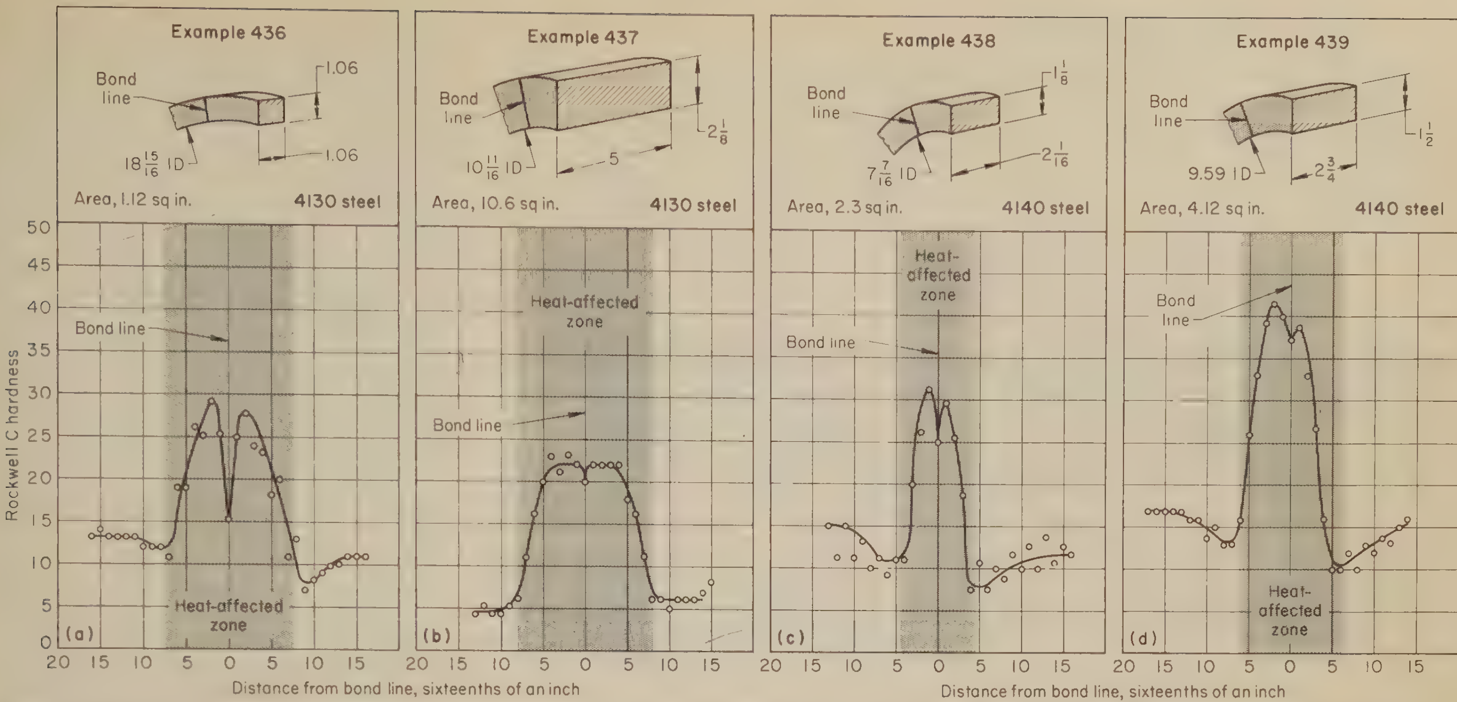
After being flash welded, the ring was heat treated to obtain increased ductility for sizing. This treatment consisted of holding at 1400 F for 1 hr, cooling to 1250 F, holding at 1250 F for 1 hr, heating to 1330 F, holding at 1330 F for 2 hr, and then air cooling. The resulting hardness was 170 Bhn max. The ring was then expanded to size and proof tested. Before final machining, the ring was quenched and tempered to Rockwell C 32 to 36.

Example 439 (Fig. 17d). A 9.59-in.-ID blank for a ring gear with the same function as that of the ring gear described in Example 438 was made from 1½ by 2¾-in. 4140 steel bar stock by roll forming and flash welding. The cross-sectional area of the joint was 4.12 sq in. Production rate was 20 rings per hour.

As shown in Fig. 17(d), the range of the as-welded hardness across the heat-affected zone was greater than for the ring in Example 438. The maximum hardness was about Rockwell C 41, or ten points higher than the maximum hardness of the ring in Example 438.

Heat treatment prior to sizing and proof testing, and final heat treatment, were the same as for the ring in Example 438.

Full heat treatment can restore a flash welded steel part to the uniform hardness of the unwelded stock, but merely tempering the hard weld metal to the original hardness of the base metal does not result in full homogeneity, because between the hardened weld metal and the unaffected



Welding condition	Example 436	Example 437	Example 438	Example 439
Initial die opening, in.	1 13/16	4 3/8	2	3 1/8
Final die opening, in.	3/4	1 3/4	3/4	1
Flash-off length (total), in.	3/4	1 7/8	7/8	1 1/2
Upset length (total), in.	5/16	3/4	3/8	5/8
Total metal lost, in.	1 1/16	2 5/8	1 1/4	2 1/8
Flashing time, sec	22	120	40	85
Clamping force, lb(a)	150,000	370,000	217,000	310,000

Welding condition	Example 436	Example 437	Example 438	Example 439
Flashing force, lb(b)	83,000	83,000	83,000	83,000
Upsetting force, lb(b)	165,000	207,000	165,000	207,000
Transformer tap setting	Series-4	Parallel-3	Series-5	Parallel-2
Upsetting kva demand (est)	175	600	240	380
Heat-control setting, %	75	80	75	75
Unclamping delay, sec	5	5	6	6
Platen-return delay, sec	2.5	2.5	2.5	2.5

(a) Maximum clamping force, 620,000 lb at 2000 psi on cylinder. (b) Maximum flashing and upsetting force, 208,000 lb at 1000 psi on cylinder.

Fig. 17. Variations in hardness across the heat-affected zones in flash welded rings that were roll formed or compression-die formed to four different inside diameters from 4130 and 4140 steel bars of various cross-sectional areas (Examples 436 to 439)

base metal there is a narrow zone that has been overtempered by the welding heat and that is softer than the original base metal. This softened zone can be brought to uniform hardness only by full heat treatment. The softened zone may or may not be detrimental to the service life of the weldment.

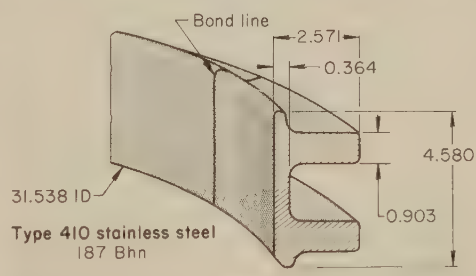
Tempering in a flash welding machine is impractical for two reasons: (*a*) it is difficult to maintain a uniform temperature in the metal between the electrodes; and (*b*) proper tempering of the edge of the heat-affected zone normally cannot be done without overtempering and softening of the areas nearest the bond line.

Strength of Welds

Because flash welds are made from the base metal without any filler metal, the welds can be made to have almost the same properties as the base metal. In welding steel, upsetting diverts the fiber of the steel from its normal direction, and this may have some effect on strength.

In tension tests, yielding often occurs on both sides of the weld before fracture takes place. Fracture occurs in the base metal if it is the softer structure, or in a region softened by the heat of welding if the base metal is hard.

When workpieces are uniformly heat treated after welding, the strength of the weld is theoretically as high as that of the base metal, except where the base metal has a relatively high



Initial die opening	3 5/8 in.
Final die opening	1 1/4 in.
Metal lost	2 3/8 in.
Preheat time	0.6 sec
Flashing time	25 sec

Fig. 18. Section of a jet-engine rear-mount ring that was made by flash welding a stainless steel extrusion rolled into a ring (Example 440)

tensile strength. If a flash welded carbon or alloy steel workpiece is heat treated so that it has a tensile strength less than about 150,000 psi, the workpiece is homogeneous throughout and may fracture either at or away from the bond line. At a tensile strength higher than about 150,000 psi, the fracture is more likely to occur at the bond line, presumably because of the removal of some carbon from the steel at the bond line during welding, or the presence of inclusions (see page 505).

In the following example, in which a stainless steel ring was annealed after flash welding, the weld had only slightly less strength than the base metal.

Example 440. Production of a Stainless Steel Ring by Roll Forming and Flash Welding an Extruded Section, in Which the Weld Was Over 98% as Strong as the Base Metal (Fig. 18)

A jet-engine rear-mount ring, a section of which is shown in Fig. 18, was made by roll forming a type 410 stainless steel (AMS 5613) extruded section, and then flash welding it into a continuous ring. The tensile strength of the welded joint was 98.8 to 99.7% that of the base metal.

The ring was welded in a 750-kva, single-phase, 440-volt machine with a maximum secondary output rating of 7500 amp at 16.9 volts. The clamping mechanism and the movable platen were hydraulically actuated. To ensure good conduction of electrical current, the 3-in.-long clamping dies were made of RWMA class 2 copper electrode material, and the clamping surfaces on the workpiece were polished to remove oxide film, scale and other contaminants that could hinder current flow.

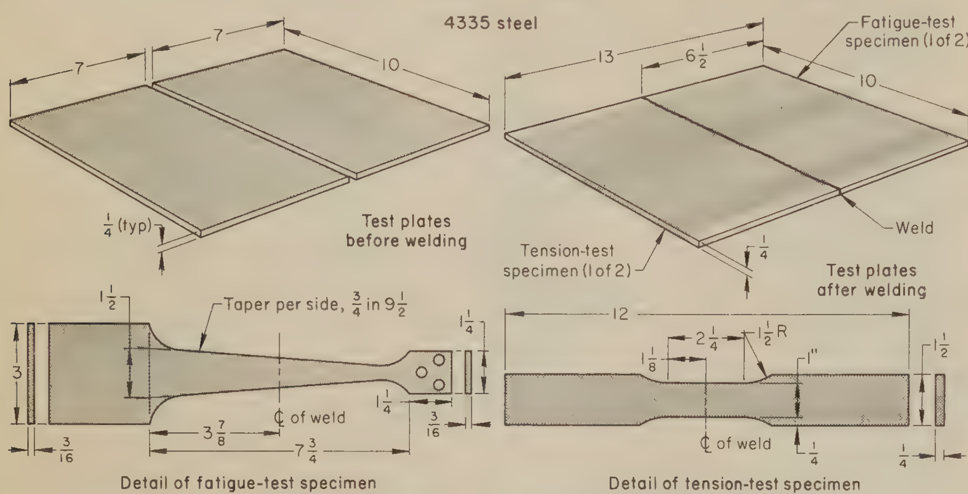
The operations for making the ring were as follows:

1. Cut extruded section to length.
2. Roll form in a horizontal three-roll forming machine equipped with rolls shaped to fit the extrusion.
3. Polish end surfaces for electrode contact.
4. Flash weld.
5. Remove flash and polish heat-affected area.
6. Anneal to 187 Bhn.
7. Size, round up, and proof test.
8. Heat treat (if required by customer).

The welded joint in each ring was proof tested in a hydraulically actuated expander that applied uniform pressure on all sections of the ring simultaneously. The proof test consisted of 1% minimum cold expansion of the metal across the weld in a 2-in. gage length. The testing operation also made the ring round and sized it to the specified inside diameter.

Table 9. Effects of Six Different Atmospheres on Strength of Flash Welds in 4335 Steel (Example 442)

Welding atmosphere	Dew point, F	Tensile strength (2 tests) Psi	Tensile strength (2 tests) % of base-metal strength	Fatigue limit Strength, psi	Fatigue limit No. of tests
Dry nitrogen, 1% oxygen	0	176,000	98	75,000	4
Butane gas	...	175,000	97	68,000	5
Dry nitrogen	20	179,000	99	...	3
Nitrogen	75	165,000	92	50,000	3
Dry nitrogen, 1% oxygen	20	166,000	92	50,000	3
Air	65	165,000	92	50,000	7



Welding Conditions for All Atmospheres

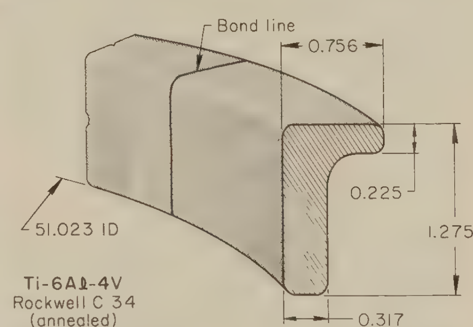
Initial die opening	1.75 in.
Final die opening	0.75 in.
Total flash-off	0.75 in.
Total upset	0.25 in.
Total metal lost	1.00 in.
Voltage, open circuit	6.5 volts
Flashing time	30 sec
Upsetting time	<0.1 sec
Upset-current time	0.3 sec
Upsetting pressure	20,000 psi

One ring from each production lot was tension tested according to AMS 7493, which covers flash welding of martensitic stainless steel. Standard ASTM tension-test specimens were used. The base metal had a hardness of 187 Bhn, tensile strength of 95,100 psi, and 29% elongation. Two test specimens taken across the weld had the following properties: hardness, 187 Bhn; tensile strength, 94,000 and 94,900 psi; joint efficiency, 98.8% and 99.7%; and elongation, 29% and 26%.

Before proof testing, all rings were inspected visually for alignment and for surface defects. Random samples were checked radiographically for internal defects in the heat-affected zone.

The use of an extruded section for the ring instead of a rectangular bar resulted in material savings of $75 per piece. There was an additional saving in machining costs, since there was less metal to remove.

Production rate was seven rings per hour, including polishing the clamping surfaces, flash welding, and removing the weld upset. Welding conditions are given in the table that accompanies Fig. 18.



Initial die opening	2⅛ in.
Final die opening	¾ in.
Metal lost	1⅜ in.
Preheat time	10 sec
Flashing time	10 sec

Fig. 19. Section of a jet-engine ring that was made by flash welding a titanium alloy extrusion rolled into a ring (Example 441)

Some of the alpha-beta titanium alloys can be strengthened by aging at moderately elevated temperatures. The rapid quenching effect of clamping dies used in flash welding suppresses the transformation of the elevated-temperature beta phase that occurs with slow cooling. Aging usually decreases the ductility of the work metal with little or no change in the hardness, as in the following example.

Example 441. Production of a Titanium Ring by Flash Welding (Fig. 19)

The ring shown in Fig. 19 was used, after machining, as a jet-engine inlet-case seal. The workpiece was an AMS 4928 (titanium alloy Ti-6Al-4V) extrusion with a hardness of Rockwell C 34, tensile strength of 145,000 psi, and 14% elongation. The welded joint had the same hardness, but a tensile strength of 151,900 psi, and elongation of 12.5%. Thus the joint efficiency was 105%. The welded area was about 0.5 sq in.

The joint was made in a 750-kva, single-phase, 440-volt flash welding machine with a maximum secondary output rating of 7500 amp at 16.9 volts. Hydraulically actuated clamps, 3 in. in length and made of high-conductivity copper (RWMA class 2), held the roll formed ring during welding. The movable platen was also hydraulically actuated.

The extruded section was cut to length, heated to 1250 F, and then roll formed into a circle in a horizontal three-roll forming machine. To ensure maximum current flow, the contact surfaces of the workpiece at the clamping dies were polished before the ring was placed in the welding machine. After welding, the weld upset was removed, the weld area was ground by hand to the same dimensions as the adjoining area, and the joint was inspected for alignment and for defects. Then the welded rings were heat treated in accordance with AMS 4928.

The joint was proof tested by placing the welded ring in a hydraulically actuated expander and applying uniform pressure to all sections of the ring simultaneously. The circumference of the ring was increased about 2 in., or 1¼%, during this operation, which also made the ring round and sized the inside diameter to specification.

One ring from each production lot was used for destructive tests on the base metal and the welded joint. The tests were conducted according to AMS 7498, which covers flash welding of titanium alloys.

The ring that was made from the extruded section weighed 15 lb, and the bar cost $145. Had the ring been made from a rectangular bar, it would have weighed 36 lb, material cost would have been $270, and machining the welded ring to final contour would have cost substantially more.

Production rate was 35 rings per hour. Welding conditions are given with Fig. 19.

Effect of Protective Atmospheres on Flash Welds

Protective atmospheres can be used to improve the quality of flash welds — especially welds in ferrous metals. Dry hydrogen, dry hydrocarbon gases, and dried inert gases such as helium, argon and nitrogen, have been used for welding ferrous metals. Reducing gases generally are better than dried inert gases. Small amounts of water vapor or oxygen in reducing or inert gases greatly reduce their effectiveness. In flash welding highly reactive metals, only helium or argon can be used as a shielding gas, although some work with these metals indicates that good welds can be made by flash welding in air. In welding aluminum alloys, the use of an inert atmosphere such as argon does not appear to improve weld quality.

The weld strengths of 4335 steel that was flash welded in air, a reducing gas, and inert gases are compared in Example 442. For flash welded 8630 steel, Example 443 compares fatigue life of welds made in air, nitrogen and butane.

High-quality welds can be made only by using optimum welding procedures. Protective atmospheres cannot compensate for the use of poor procedures.

In flash welding, the value of a protective atmosphere depends on how effectively it is applied. Tubular sections are relatively easy to protect by introducing the gas inside the tube and allowing it to escape only through the flashing edges, as was done in Example 444. Long, flat sections are difficult to protect, because they require complete enclosure, which is difficult to design and to work with.

In the following example, steel plates were flash welded in different atmospheres to determine the effects of the atmospheres on strength of welds.

Example 442. Effects of Six Different Atmospheres on Strength of Flash Welds in 4335 Steel (Table 9)

A series of 4335 steel plates was flash welded, under the conditions given in Table 9, in six different atmospheres to compare the effects of the atmospheres on weld strength. Gas atmospheres (except for air) were confined at joint areas by means of a 0.06-cu-ft box-type brass enclosure with asbestos seals. After welding, upset metal was removed and the plates were heat treated to a tensile strength of 180,000 psi. Specimens were then machined for transverse-weld tension and fatigue testing.

Dimensions of the test plates, and of the fatigue-test and tension-test specimens, are shown in the illustration with Table 9.

Results of the tests, which are given in Table 9, show that tensile strength of welds made in dry hydrogen, in butane and in dry nitrogen was 5 to 7% greater than that of welds made in air. When water vapor or a small quantity of oxygen was added to dry nitrogen, tensile strength was not significantly greater than when welding was done in air.

The fatigue-test results were more pronounced. Specimens welded in dry hydrogen showed a 50% increase in fatigue strength over those welded in air; those welded in butane showed a 36% increase. The results for dry nitrogen were inconclusive. However, as in the tension tests, when water vapor or a small amount of oxygen was added to dry nitrogen, there was no improvement over welding in air.

The Krause push-pull fatigue test was used for testing the weld specimens. Ten million cycles were used to determine the limits given in Table 9.

Tests indicate that, compared with air, protective atmospheres improve the fatigue life of flash welds in 8630 steel tubing, as in the next example.

Example 443. Fatigue Life of Welds Made in Air, Nitrogen and Butane

Ambient air, dry nitrogen, and butane were compared as to their effects on the fatigue life of flash welds in 8630 steel tubing. The tubing had an outside diameter of 2⅝ in. and a wall thickness of 0.192 in. For welding in nitrogen and butane, one end of the tubing was sealed, and the gas was introduced from the opposite end at a slight positive pressure to produce a continuous flow across the joint interface. The nitrogen flowed at a rate of about 2.5 cfm, and the butane, at a rate that maintained a constant flame at the flashing edges. No special arrangement was made for welding in air. Dry nitrogen, with a dew point of about 20 F, was supplied in a standard compressed-gas cylinder. The butane was used as it boiled from the liquid state in a standard LP gas tank, and thus was inherently free of water vapor. After welding, the upset metal was removed from the inside and outside of the tube, and the tube was heat treated to a tensile strength of 190,000 to 200,000 psi.

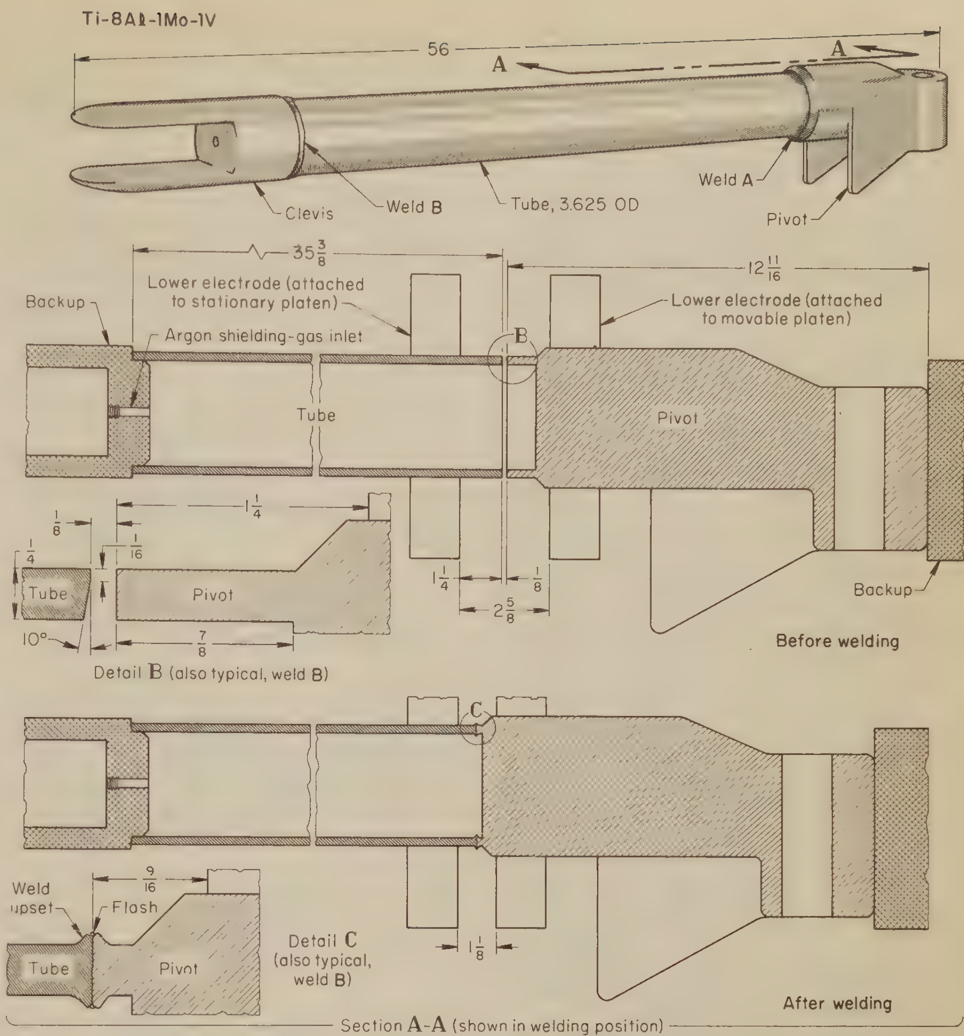
The welded tubes were then subjected to a fatigue test using a rotating beam with constant deflection, which developed a maximum fiber stress of 115,000 psi in the welds. Fatigue life of the welds made in the three atmospheres was as follows:

Welding atmosphere	Dew point, F	Cycles to failure	Number of specimens
Air	65	10,290	9
Dry nitrogen	20	11,050	4
Butane	..	56,800	5

In the following example, titanium alloy forgings were flash welded to each end of a length of tube made of the same alloy. During welding, the heated metal was protected from contamination by purging the inside of the tube with argon gas.

Example 444. Shielding a Flash Weld in a Titanium Alloy by Purging the Inside of a Tubular Section With Argon Gas (Fig. 20)

The components of the drag strut shown in Fig. 20 were made from two titanium alloy forgings (Ti-8Al-1Mo-1V) and a length of tube of the same alloy. The workpieces were joined by flash welding in two setups. During welding, the work metal was protected from contamination by introducing argon into the tube and allowing it to escape through the flashing edges. For the first weld, the argon was fed into the tube through an inlet in the fixture



Initial die opening	2⅝ in.	Total metal lost per weld	1⅜ in.
Final die opening	1⅛ in.	Flashing current	34,100 amp
Initial gap	⅛ in.	Flashing voltage	4 v
Platen travel:		Flashing time	15 sec
Manual flashing	⅛ in.	Upsetting time	10 sec
Automatic flashing	¾ in.	Current flow after start of upset	7 cycles
Upsetting	⅝ in.	Postheat time	7 cycles
Total	1½ in.	Shielding gas	Argon

Fig. 20. Drag strut made by flash welding two Ti-8Al-1Mo-1V titanium alloy forgings to the ends of a tube made of the same material, under the conditions given in the table, and setup for gas shielding and flash welding one of the joints (Example 444)

backup that supported the tube end (see section A-A in Fig. 20). A hole through the clevis forging provided a means for introducing the argon into the tube for the second weld.

The ends of the forgings and the tube were machined in the weld area and cleaned with a solvent before flash welding. The counterbore in each forging provided a weld area that matched that of the tube. The ends of the tube were chamfered as shown in Fig. 20 so that flashing would start near the outer surface.

The workpieces were not preheated, but the flashing current was permitted to flow for seven cycles after upsetting started, to ensure proper upsetting temperature. After upsetting was complete, the welds were postheated for seven cycles.

Weld specimens were tension tested to verify the suitability of the welding conditions listed in the table with Fig. 20. The flash welded joint in the test specimens had an average tensile strength of 142,000 psi; the base metal had a tensile strength of 143,000 psi.

The procedure for qualifying the machine settings followed the requirements of MIL-W-6873, which covers flash welding of carbon and low-alloy steels.

The welding machine had a rating of 800 kva and a maximum upsetting force of 200,000 lb. The platen was cam-actuated through a cam ratio of 1½ to 1.

Suitability of Welds for Forming

The upsetting action that occurs in flash welding not only forces molten metal and oxide impurities out of the weld but also produces a microstructure resembling that of a forging. The grain structure at the bond line is essentially the same as that of the heat-affected zone on either side of the bond line, except for size.

The high ductility of flash welds in low-hardenability metals permits subsequent cold forming operations of varying degrees of severity without postweld heat treatment. Cold rolling, cold bending, spinning, hot forming and wiredrawing also can be applied to flash welded products.

The automotive wheel rim in the following example was made from low-

carbon steel by flash welding at a high production rate. The flash welded band was roll formed cold without prior heat treatment and with no fracturing of the weld that could cause air leaks.

Example 445. Production of a Rim for an Automotive Wheel (Fig. 21)

The rim portion of an automotive wheel, shown in Fig. 21, was made from 1012 steel strip stock by automatically flash welding a ring-rolled band, then progressively roll forming the cross-sectional contours. The surface of the rolled ring was shot blasted before welding.

The input rating of the flash welding machine was 600 kva, 440 volts, single-phase, 60 cycles. The maximum output rating of the secondary was 2000 amp at 15 volts. The current used for this workpiece was 1800 amp at 12 volts.

The movable platen was actuated by a cam mechanism. Clamping dies were made of RWMA class 3 electrode material. An air cylinder, using an air pressure of 70 psi, applied the clamping force on electrodes ⅝ in. wide by 8½ in. long with knurled or serrated surfaces. The unformed flat areas along the abutting edges of the band, which are common in roll forming, extended on both sides of the jaws and facilitated clamping and ensured alignment of the abutting edges.

A strip 43⅛ in. long was sheared from the coil and was automatically transferred to a ring-rolling station, and then to the welding station. The ends of the circular strip were gripped and forced together under high pressure during welding. Metal lost during flashing and upsetting was approximately ⅜ in. The coil stock was 0.130 in. thick and $8\frac{7}{16}$ in. wide.

After the weld upset was scarfed, the band passed through a bath of lubricating oil and into a series of four forming rolls and an expander that progressively formed the band into the cross-sectional shape shown in Fig. 21. After the contour roll forming operation, portions of the finished rim were as much as 25% greater in diameter than the flash welded band.

The completed rim was then degreased, dried and conveyed to a station where an operator placed the spider into the rim. The assembly was moved automatically to a press where the spider was press fitted into the rim for resistance spot welding (for a description of that welding operation, see Example 373, on page 408).

The completed wheel assembly was visually and mechanically inspected for weld integrity and dimensional accuracy. To withstand the forming operations, the flash weld had to be free from pinhole defects caused by sulfur, aluminum, or slag in the steel. Pinholes are also caused by a cold weld or by discontinuous flashing. The finished rim had to have an airtight joint to maintain inflation of the tire.

Production rate was 720 rims per hour. Welding conditions are given in the table that accompanies Fig. 21.

Increased speeds of cold rolling mills and wiredrawing mills have resulted in the production of a higher percentage of off-gage strip and wire while the mills are accelerating and decelerating. The need for uniformity of thickness and for larger coils has led to the adoption of flash welding for joining the ends of several small coils into one large coil before the stock is reduced in thickness or diameter. In these applications, the weld must approach very closely the characteristics of the base metal without varying in uniformity and must be able to undergo the same deformation by cold reduction. In the following example, flash welded joints were reduced in diameter by wiredrawing as easily as was the base metal.

Example 446. Joining of Aluminum Alloy Rods by Flash Welding To Allow a Continuous Wiredrawing Operation

Aluminum alloy 5056-O rods, ⅜ in. in diameter, were joined by flash welding to permit continuous wiredrawing. The high joint efficiency and consistently high quality of flash welds permitted the rods to pass through five drawing operations with a minimum of downtime due to breakage.

The die diameter and reduction in area of the rods for each wiredrawing operation were as follows:

Operation No.	Die diameter, in.	Cross-sectional area, sq in.	Reduction in area, %
1	0.296	0.0688	37.7
2	0.234	0.0430	37.5
3	0.196	0.0302	29.8
4	0.168	0.0222	26.5
5	0.120	0.0113	49.0

Pinch-type dies were used to ensure high-quality welds and to assist in removing the weld upset. The welding conditions were as follows:

Initial die opening ....0.760 in.
Final die opening ....0.010 in.
Flash-off length, total ....0.500 in.
Upset length, total ....0.250 in.
Flashing velocity ....0.25 in. per second
Upsetting velocity ....5 in. per second
Flashing time ....2 sec
Upsetting time ....0.05 sec (3 cycles)
Open-circuit voltage ....12.6 v
Clamping force ....6500 lb
Upsetting force ....3200 lb

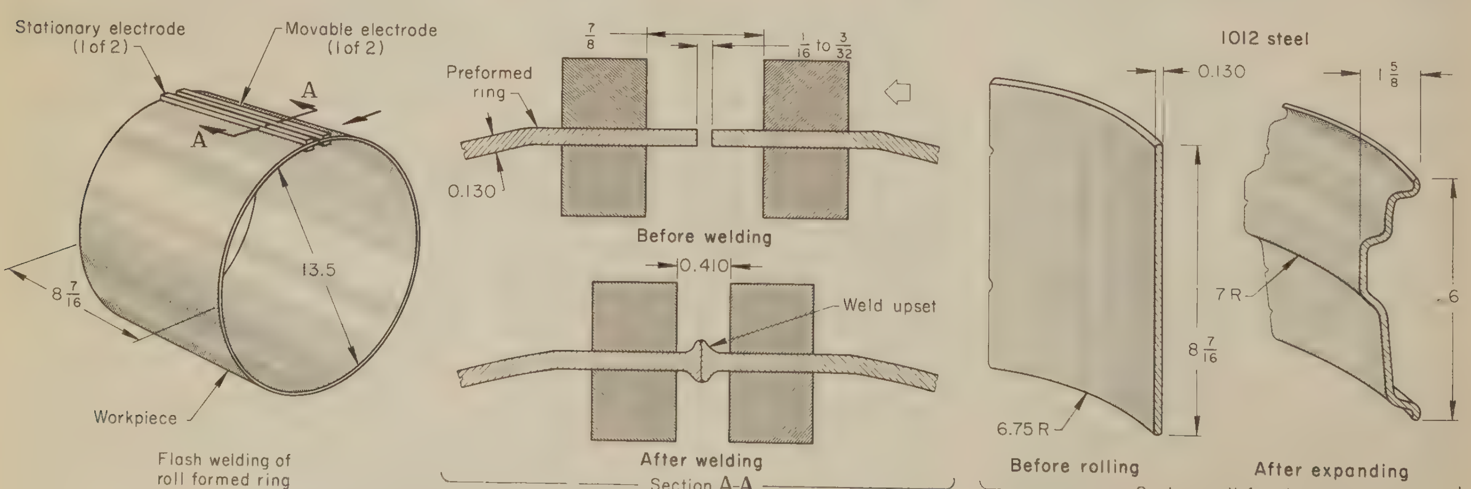
Causes and Prevention of Weld Defects

Common defects in flash welds include: circumferential crevices at the bond line that appear after removal of the upset; cracking caused by brittleness in the heat-affected zone; cast metal in the weld; voids, oxides and inclusions in the weld; and intergranular oxidation and decarburization in the heat-affected zone.

Circumferential Crevices. If either heating or upsetting is insufficient, bonding will not extend across the entire workpiece and into the weld upset, and removal of the weld upset will reveal the presence of an unwelded area in the workpiece at the joint. Such a crevice indicates that a 100% bond has not been obtained, and that the strength of the workpiece may be less than minimum requirements. This type of defect usually can be prevented by the use of greater upsetting pressure or the use of more heat, or both.

Cracking in the heat-affected zone, caused by rapid cooling, can be minimized by releasing the electrodes immediately after upsetting and transferring the workpiece to a furnace for temperature equalization and controlled cooling. After the workpieces have been uniformly heated in the furnace, they can be buried in lime, powdered mica or asbestos feathers to ensure slow cooling. If a furnace is not available and the workpieces are of carbon steel, the weld can be reheated in the welding machine by passing current through the finished weld until a dull-red color is seen. Then the current is turned off, the electrodes are quickly unclamped, and the workpiece is buried in lime or other insulating material for slow cooling.

In the flash welding of parts made of dissimilar steels, such as welding of high speed steel drills to medium-carbon steel shanks, slow cooling must be ensured to avoid cracks in the steel of higher hardenability. New drills made by flash welding normally are fully heat treated after welding. When drills are repaired, or are made longer by flash welding a short drill to a shank extension, rehardening after welding



Initial die opening, ⅞ in.; final die opening, 0.410 in. min.; initial extension per piece, $1\frac{3}{32}$ in.; total metal lost, ⅜ in.; output current, 1800 amp at 12 volts; flashing and upsetting time, 90 cycles (1.5 sec)

Fig. 21. Setup for flash welding, and results of contour roll forming, a 1012 steel band in production of an automotive wheel rim (Example 445)

may not be feasible, and slow cooling is necessary — not only to prevent cracking, but also to minimize brittleness in the weld zone. Such brittleness could lead to failure of the tool in service. In a few applications, the parts to be welded are furnace preheated, welded, and immediately furnace heat treated to prevent cracking.

Cast Metal in the Weld. A certain amount of molten metal forms at the weld faces during flashing and should be extruded from the weld during upsetting, leaving the weld area in a homogeneous condition. However, pockets of molten metal sometimes are trapped in the weld and appear as cast metal under a microscope. Because cast metal is likely to contain small shrinkage cracks and is of lower ductility than worked metal, its presence should be reduced to a minimum.

Cast metal may be trapped in welds between dissimilar alloys that have widely differing hot compressive strengths. The metal or alloy with the lower hot compressive strength upsets to a greater degree, and so entraps cast metal in the weld. Metals with high electrical resistivity become hotter during welding, increasing the probability of formation of cast metal.

Voids frequently are formed when the piece being welded is too large for the welding machine and the upset pressure is insufficient to close all the craters formed during flashing. Sometimes, molten metal formed at the weld interface may be extruded into a void during upsetting, and can be seen under the microscope as a globule of cast metal in the void.

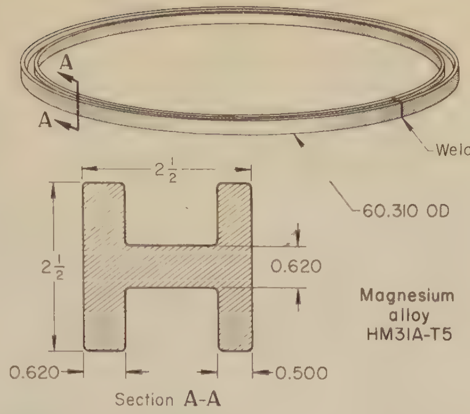
Oxides and other inclusions may be present in joints that have been welded with insufficient upsetting force to expel them, or at too low a temperature to give plasticity to the weld region. Inclusions are very small but they weaken the weld, and heat treatment does not remove them or improve the properties of the weld.

Another type of inclusion is referred to as a penetrator. Penetrators are more prevalent when a high flashing voltage is used, and are caused by large temperature gradients, occluded gas, and nonmetallic inclusions that are trapped in craters in the flashing surface during upsetting. The occurrence of penetrators can be minimized by using the correct voltage, platen speed and flashing gap, and using a protective atmosphere.

Decarburization. During flash welding, high-carbon steel loses carbon along the flashing surfaces, especially when welding is done in air or in an atmosphere of moist gas. The decarburized metal is not entirely expelled during upsetting and some remains in the weld as a zone of weakness.

Intergranular oxidation ("burning") generally is caused by improper material extension during welding of dissimilar metals. Sufficient heat can be developed to oxidize the metal at a point behind the weld. Sometimes, oxidation can cause the workpieces to fall apart in the oxidized region.

Improper contact between the electrode and the workpiece can cause a locally melted or burned area beneath the electrode.



Initial die opening	3¼ in.
Final die opening	1/16 in.
Initial extension per piece	1⅝ in.
Total metal lost	3 3/16 in.

Fig. 22. Ring that was made by flash welding a formed magnesium alloy extrusion (Example 447)

Flash Welding vs Alternative Processes

In some applications, flash welding is the best joining method regardless of the quantity of parts to be produced. Other parts that can be produced by flash welding can be produced equally well by other joining processes, or by forging.

In the following example, the alloy specified was not available as a forging, and flash welding was the only joining process that could produce welds with properties equal to 90% of those of the base metal.

Example 447. Flash Welding of Extruded Magnesium Alloy Rings (Fig. 22)

Flash welded rings, such as the one shown in Fig. 22, were fabricated from H-shape magnesium alloy HM31A-T5 extrusions. The welds were required to have tensile properties equal to 90% of the minimum specifications of the base metal, without subsequent heat treatment. Flash welding was the only joining process that could meet this requirement.

An extruded shape was used instead of a rectangular bar, to minimize finish machining. The magnesium alloy extrusions conformed to AMS 4389, which specifies minimum tensile strength of 37,000 psi and minimum elongation of 4%.

The rings were made in the following seven operations:

1. The extruded shape was formed into an open ring of approximately the finished diameter, with special tooling in a 30-ton hydraulic forming machine at a forming temperature of 750 F.
2. The open ring was band sawed to the proper circumference, allowing stock for flash-off and upset. The as-sawed edges were suitable for welding and needed no further preparation.
3. After preheating the ends of the ring and the steel clamping dies, the ring was flash welded.
4. The weld upset was removed flush with the base metal by snag grinding.
5. The welded ring was heated in a furnace and expanded to size in a sizing and flattening fixture. This operation also proof tested the joint.
6. The weld was inspected using the dye-penetrant method.
7. A ring was machined from each welded ring, and a specimen was cut from it for tension testing across the weld.

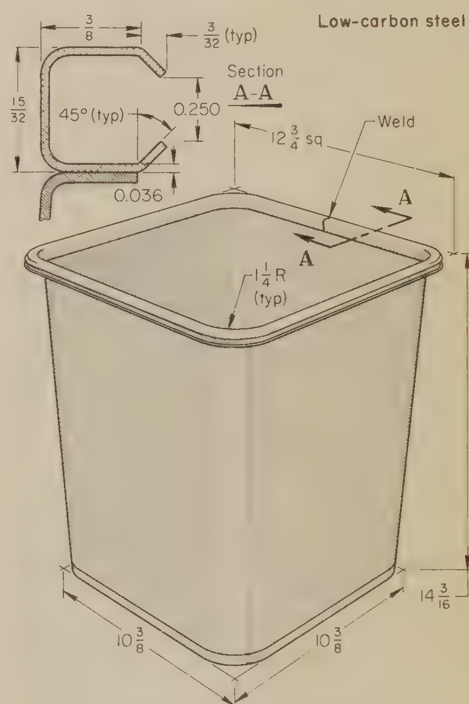
The specification for proof testing the welded joint required that the base metal and the metal in the heat-affected zone be elongated a minimum of 1%. Because the heat-affected metal was more ductile than the base metal, the heat-affected metal required an elongation of about 1½% between gage points to correspond to an elongation of 1% in the base metal.

The welding machine had an input rating of 1600 kva, a maximum secondary output rating of 160,000 amp at 25 volts, and a platen force of 500 tons max. The actual welding current used was 60,000 amp at 9 volts. The clamping dies were made of O1 tool steel machined to the diameter of the ring and the contour of the extrusion. Pinch-type dies were used to obtain more consistent weld quality and to trim the weld upset.

A 500-ton hydraulic press was used to apply pressure on a segmented sizing die.

The tension-test specimen was cut in a boring mill. The results of the tensile test showed that the weld area had mechanical properties between 90% and 100% of the minimum specifications of the base metal. Tensile elongation of the test specimens ranged from 5% to 10%.

In the following example, torch brazing was replaced by flash welding to increase production rate from 144 to 275 pieces per hour. In addition, the improved quality of welded joints obtained by using flash welding greatly reduced the rejection rate.



Comparison of Production Rates

Torch brazing(a)	144 pieces per hour
Flash welding(b)	275 pieces per hour

Conditions for Flash Welding

Initial die opening	1⅝ in.
Final die opening	1¼ in.
Initial extension per piece (max)	¾ in. per side
Flash-off length, per piece	1/16 in.
Upset length, per piece	1/16 in.
Total metal lost	¼ in.

(a) Sequence of operations: position in fixture; apply flux; apply torch to heat; braze; cool and soak off flux; dry and apply rust preventive; belt-sand and grind. (b) Sequence of operations: position in welding machine; weld; belt-sand and grind.

Fig. 23. Wastebasket for which production rate was increased when method of joining contour roll formed top channel was changed from torch brazing to flash welding (Example 448)

Example 448. Change From Torch Brazing to Flash Welding To Increase Production (Fig. 23)

The low-carbon steel top channel for a wastebasket, shown in Fig. 23, was made by bending a contour roll formed section into an open square-shape loop and joining the ends by torch brazing. The channel was then spot welded to the basket body and painted, and a plastic bumper surrounding the basket was installed in the open legs of the channel. The process for making the butt joint was changed to flash welding because, with brazing, two shifts of eight hours each were unable to supply enough channels for one shift of basket production.

The 0.036-in.-thick cold rolled low-carbon steel strip was contour roll formed in a four-pass mill and was cut to length in a flying cutoff shear. The channels were formed two at a time in a powered tube-bending machine, and were then placed in a fixture for brazing. After the metal around the brazed joint had cooled, the loop was placed in hot water to dissolve the flux, or to soften it for removal. After the flux was removed, the part was dried and a rust preventive was applied to the inner and outer surfaces. The excess brazing filler metal was removed from the outer surfaces of the channel with a belt sander, and from the inner surfaces with a thin grinding wheel.

The flux used was AWS type 5 (borax), and the filler metal was RCuZn-C, a low-fuming material.

Both the production rate and the quality of the joint surface after removal of the excess brazing filler metal were important factors in considering another process.

When the joining process was changed to flash welding, the same basic manufacturing sequence was followed. However, since the loops were not dipped in water, a rust-preventive coating was not needed. The time required for cleaning the welded workpiece was greatly reduced, and only two operators were needed for this work, instead of three.

The input rating of the flash welding machine was 110 kva, 220 volts, single phase, 60 cycle, with 20-kva demand at 50% duty cycle. The transformer had a series-parallel winding and four taps. The parallel winding and the No. 4 tap were used, producing the maximum secondary current of 22,000 amp at 4.4 volts.

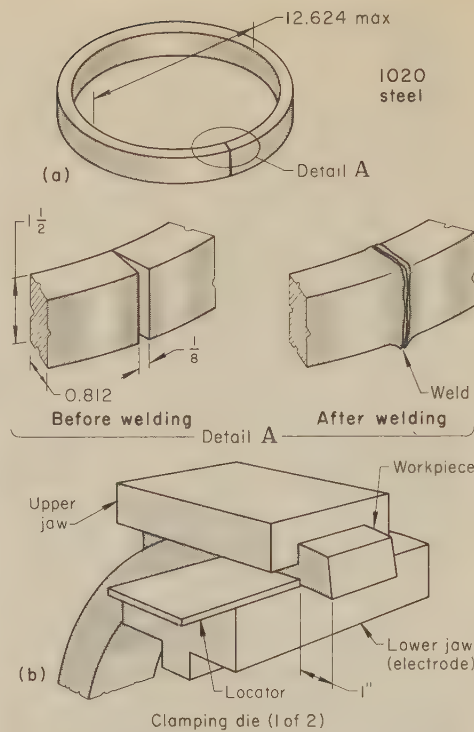
Special air-actuated dies were used to clamp the workpiece in the machine. The movable platen was also air-actuated, and could exert about 125 lb of force. The upper dies were made of RWMA class 3 electrode material, and the lower dies were made of an oil-hardening tool steel.

The flash welded joints were of high quality, and rejections were almost nil. Testing was done by dropping a welded part from a height of 36 in. onto a steel plate. The production rate was 275 pieces per hour, compared with 144 per hour when the joints were brazed. Sequence of operations for both processes, and conditions for flash welding, are given in the table that accompanies Fig. 23.

Forging is a common method of producing rings in any forgeable alloy, but metals that scale easily have a sizable material loss during forging. In the following example, three-roll forming and flash welding of bar stock were used to produce rings of a quality equal to those made by forging.

Example 449. Change From Forging to Three-Roll Forming and Flash Welding To Produce a Ring (Fig. 24)

The fin-ring blank shown in Fig. 24 originally was machined from a forged ring. When the method of manufacturing the blank was changed to three-roll forming and butt welding, flash welding was chosen as the joining process to minimize slag and oxide particles in the joint. Weld quality was checked radiographically.



Sequence of Operations

1 Die cutoff bar to length
2 Three-roll form the ring
3 Press form mating areas
4 Flash weld
5 Remove weld upset
6 Size inside diameter

Welding Conditions

Initial die opening	2 in.
Final die opening	1¼ in.
Initial extension per piece	1 in.
Flash-off length, total	½ in.
Upset length, total	¼ in.
Total metal lost	¾ in.

Fig. 24. Fin-ring blank that was flash welded in the setup shown (Example 449)

Table 10. Time and Costs for Flash Welding vs Gas Tungsten-Arc Welding of Forty Stainless Steel Rings (Example 450)

Item	Gas tungsten-arc welding	Flash welding
Welding time, minutes	3.75	1.7
Total time, minutes(a)	8.00	6.6
Cost Comparison		
Labor ($3 per hour)	$0.40	$0.33
Welding supplies(b)	0.50	None
Work-metal loss	None	0.40
Total	$0.90	$0.73
Savings for 40 rings		$0.17

(a) Includes loading, unloading and scarfing. (b) Includes the cost of 17-7 PH filler wire, inert gas for shielding, and tungsten electrodes.

The rolled ring was made of special-quality 1020 steel that met specification QQ-S-631. Bar stock size was 13⁄16 in. thick by 1½ in. wide by 42½ in. long. In three-roll forming a bar, a short length on each end of the bar cannot be formed, so to maintain alignment during flashing and upsetting, the butted ends were press formed after rolling. Detail A in Fig. 24(a) shows the butted ends of the ring before and after welding.

The input rating of the welding machine was 250 kva, 440 volts, single phase and 60 cycles. The maximum secondary output rating was 84,000 amp at 7.8 volts. The transformer had eight taps, and No. 6 was used for this operation. Heat control was available, but was not used. The machine was loaded and unloaded manually, but the welding cycle was automatic. The maximum available force on the platen was 40,000 lb. The platen opening was 4 in. max and 1¼ in. min.

The workpiece was held in serrated jaws about 3 in. wide (contact area of 2.4 sq in.). The jaws were closed with a cam, which was operated by an air cylinder. The lower jaws, which conducted the current to the work metal, were made of RWMA class 3 electrode material, and were machined to the inside diameter of the ring. A lower locating gage positioned the workpiece on the lower jaws. The upper jaws were made of A2 tool steel and were mounted in a holder fastened to the clamping arm. A slot in the upper jaws that was machined to the outer contour of the ring clamped the workpiece to the lower jaws and prevented mismatch.

The arrangement of the clamping jaws is shown in Fig. 24(b).

The platens on which the lower jaws were mounted were made of an electrically conductive material. The movable platen was actuated by a hydraulic cylinder that had a nitrogen-gas-filled accumulator in the circuit. The platen speed was controlled by a rotary cam.

A two-station die with high speed steel cutters was used to remove the weld upset. The welded ring was sized by expanding it approximately ⅛ in. to an inside diameter of 12.604 ± 0.020 in.

The quality of the finished product was ensured by having the steel mill certify the work metal and by carefully inspecting ring size and alignment of the ends before welding. For each shipment of bar stock, a test coupon containing a welded joint was used to verify that the weld was stronger than the base metal. Also, each weld was examined radiographically.

Average time for flashing and upsetting was 0.26 min. Production rate was 65 welds per hour. Cost for labor and overhead was $0.135 per weld. Sequence of operations and welding conditions are given in the table that accompanies Fig. 24.

Many factors enter into the total cost of a particular welding process. In the following example, manual dexterity of the operator and the differentials between work-metal and welding-supply costs for each method were the principal factors in cost analysis.

Example 450. Comparison of Costs for Flash Welding vs Gas Tungsten-Arc Welding a Stainless Steel Ring (Table 10)

Costs were compared for butt welding the stainless steel ring described in Example 433 and illustrated in Fig. 12 by gas tungsten-arc welding and by flash welding.

Weld properties were not major factors in this comparison, because both welding processes developed heat-affected zones that responded favorably to subsequent heat treatment, and produced equally strong joints.

Many of the manufacturing steps were the same for both processes. The coiled strip was uncoiled, straightened, pierced, sheared to length, formed into a ring and edge trimmed before welding. After welding, both types of welds required comparable time for removal of weld flash and buildup.

The average cost per piece for each welding operation was affected by differences in setup and in level of operator skill. Costs of work metal and welding supplies also affected the total cost, as shown in Table 10. The 50-kva flash welding equipment cost about $10,000 installed, and the arc welding machine and equipment cost about $9000.

The fixture for the gas tungsten-arc welding equipment had space for 40 rings, and 40 was used as the lot size for comparing the costs of the two processes. Costs for making the rings by each process are given in Table 10.

Friction Welding

*By the ASM Committee on Flash, Friction and Stud Welding**

FRICTION WELDING is a process in which the heat for welding is produced by direct conversion of mechanical energy to thermal energy at the interface of the workpieces without the application of electrical energy, or heat from other sources, to the workpieces. Friction welds are made by holding a nonrotating workpiece in contact with a rotating workpiece under constant or gradually increasing pressure until the interface reaches welding temperature, and then stopping rotation to complete the weld. The frictional heat developed at the interface rapidly raises the temperature of the workpieces, over a very short axial distance, to values approaching, but below, the melting range; welding occurs under the influence of a pressure that is applied while the heated zone is in the plastic temperature range.

Friction welding is classified as a solid-state welding process, in which joining occurs at a temperature below the melting point of the work metal. If incipient melting does occur, there is no evidence in the finished weld, because the metal is worked during the welding stage.

A section through a friction weld joining two dissimilar steels is shown in Fig. 1. The steel with the greater forgeability has the greater amount of weld upset. When similar metals are friction welded, the amount of weld upset is about the same on both sides of the bond line.

Applications. Friction welding has been used in high production of hollow precombustion chambers for diesel engines, in welding trunnions to mounting blocks for air and hydraulic cylinders, in welding connectors to piston rods, and in fabricating track-roller hubs and ball-shaft linkages.

In the automotive industry, friction welding is used in fabricating drive shafts, axles, steering shafts and bimetal valves, and for joining hubs to gears. Another application is welding bar stock to small forgings or to plate to produce parts that would otherwise be forged. Blanks for cutting tools are made by welding low-carbon or low-alloy steel shanks to tool steel bodies.

Jet-engine parts are made by welding components made of a heat-resisting alloy to components made of a hardenable or wear-resistant alloy.

Welding Methods. There are three methods of joining workpieces by friction welding: (*a*) conventional friction welding, (*b*) inertia welding, and (*c*) flywheel friction welding.

In conventional friction welding, mechanical energy is converted to heat energy by rotating one workpiece while pressing it against a nonrotating workpiece. After a specific period of time, rotation is suddenly stopped and the pressure is increased and held for another specified period of time, producing a weld.

In inertia welding, the workpiece component that is to be rotated is held in a collet-chuck – flywheel assembly. The assembly is then accelerated to a predetermined speed, at which time the flywheel is disconnected from the power supply and the workpieces are brought into contact under a constant force. Flywheel energy is rapidly converted to heat at the interface, and welding occurs as rotation ceases.

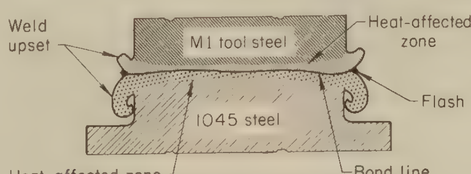
Flywheel friction welding incorporates features of both the conventional and the inertia processes. Flywheels are connected to the drive motor and to the spindle, and are coupled through an integral clutch. The drive-motor – flywheel system rotates continuously and is coupled to the flywheel-spindle system to bring the rotating workpiece to the proper speed. The motor flywheel is disengaged from the spindle flywheel after the desired energy has been extracted. The spindle flywheel, having a low moment of inertia, comes quickly to rest without braking, to complete the weld.

Process Capabilities

Many ferrous and nonferrous alloys can be friction welded. Friction welding also can be used to join metals of widely differing thermal and mechanical properties. Often combinations that can be friction welded cannot be joined by other welding processes because of the formation of brittle phases that would make such joints unserviceable. The submelting temperatures and short weld times of friction welding allow many combinations of work metals to be joined.

End preparation of workpieces, other than that necessary to ensure reasonably good alignment and to produce the required length tolerance for a specific set of welding conditions, is not critical. Frictional wear removes irregularities from the joint surfaces and leaves clean, smooth surfaces heated to welding temperature. In some applications where weld integrity is important, a small projection at the center of one of the weld members is used to ensure proper heating and forging action, and to eliminate center defects. This projection is especially helpful in welding large-diameter bars.

Automatic loading and unloading of the welding machines permit high production rates. For instance, bimetal valves are produced two-at-a-time at a rate of 1200 per hour.



The greater amount of weld upset occurred in the 1045 steel because of its greater forgeability. When workpieces made of the same or closely similar metal are welded, approximately equal amounts of weld upset are formed on both sides of the bond line.

Fig. 1. Cross section through a friction weld joining two dissimilar steels

Other advantages of friction welding include the following:

1. Flux, filler metal or protective atmospheres are not needed.
2. Electric-power and total-energy requirements are a fraction of those needed for other welding processes.
3. The operation is relatively clean, there is little spatter, and no arcs, fumes or scale are developed.
4. The heat-affected zone is very narrow and has a grain size that frequently is smaller than that in the base metal.

Limitations of friction welding are:

1. One workpiece must be round (or nearly round) at the interface and must have a size and shape that can be clamped and rotated. (Hexagon-shape bars have been friction welded to billets.)
2. Workpieces must be able to withstand the torque and axial pressure imposed during heating and forging. (See "Sections Welded", on the next page.)
3. Workholding devices must be strong enough to withstand heavy shock and torque loads.
4. The process is restricted to flat and angular butt welds that are concentric with the axis of rotation (see Fig. 13).
5. Conventional friction welding machines require expensive modifications to be able to weld workpieces that must have final angular alignment.

Economy in Operation and Material. Friction welding can be done at high production rates, and therefore is economical in operation. In applications where friction welding has replaced other joining processes, the production rate has been substantially increased. For instance, in Example 461, production rate was increased from 3 to 30 welds per hour when friction welding replaced pressure gas welding.

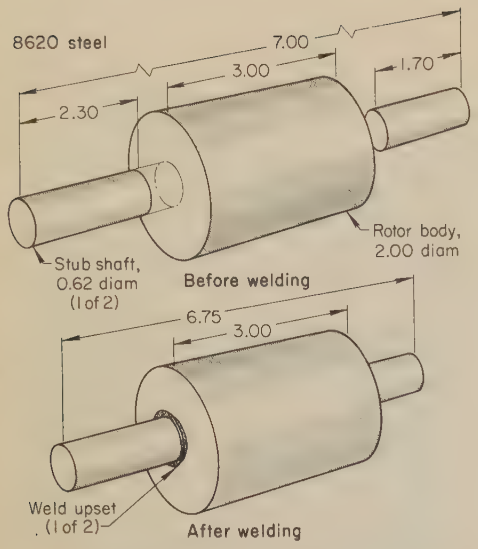
Savings in material also can be realized by the use of friction welding. In Example 454, ¾ in. less metal was needed in friction welding than in flash welding. Also, as described in Example 460, considerable metal was saved by friction welding two pieces of 4140 steel together to make a square-head bolt instead of machining the bolt from a single piece.

Substantial savings in material and machining time can be realized by using friction welding to join stub shafts to large-diameter rotor bodies or other rotating members, or to join components of valve stems — as in the applications described in the two-part example that follows.

Example 451. Changes From Machining Complete From Bar to Friction Welding of Machined Components, for Lower Metal and Machining Costs

Example 451a — Rotor Blank (Fig. 2). A blank for an air-motor rotor (Fig. 2) was made from 8620 steel by joining stub shafts to the ends of the main body by conventional friction welding. In finish machining of the welded blank, the diameter of each of the three pieces was reduced by only 0.060 in., which illustrates the concentricity to which parts can be friction welded. The use of

*For committee list, see page 485. About half of the examples in this article were contributed by members of other Metals Handbook welding committees.



Conditions for Friction Welding	
Spindle speed	2400 rpm
Axial force:	
Heating	2480 lb
Welding	4400 lb
Heat-and-weld time	45 sec per part
Weld area	0.31 sq in. per weld
Metal lost(a)	0.125 in. per weld
Production rate	65 parts per hour

(a) Total axial shortening of the workpieces during welding.

Fig. 2. Rotor blank made by friction welding three pieces instead of by machining from solid bar, to reduce work-metal and machining costs (Example 451a)

friction welding resulted in a 20% material saving and a 39% reduction in machining costs compared with the original method, which was machining from a solid bar.

Time for making the two welds, one at a time, on each rotor blank was 45 sec. The welding machine was manually loaded and unloaded and was equipped with manually actuated chucks for gripping the workpieces. Conditions for friction welding are given in the table that accompanies Fig. 2.

Example 451b — Valve Stem (Fig. 3). The use of friction welding reduced material and machining costs in the manufacturing of the bronze valve stem shown in Fig. 3. Originally, the valve stem was machined complete from a ⅝-in.-diam bar. By friction welding two pieces together and producing a weld upset large enough to provide material from which the flange could be machined to the required final dimensions (see Fig. 3), machining time was reduced 95% and material loss was reduced 98%. The friction weld was made in 7 sec, using a spindle speed of 2200 rpm, a heating pressure of 14,000 psi (about 2100 lb) and a welding pressure of 65,000 psi (about 9750 lb). Total axial shortening of the workpieces during upsetting was 0.150 in. Production rate was 180 valve stems per hour.

Weld Strength. For most metals, the strength of a friction welded joint is about the same as that of the base metal. The metal at the weld interface is hot worked, which refines the grain structure. During the final portion of the weld cycle, upsetting and extrusion of flash ensures removal of oxidized metal that may have been produced during heating. This flash usually appears in the valley at the intersection of the two weld upsets (see Fig. 1).

The relatively large unheated areas adjacent to the joint extract heat quickly from the small mass of the heat-affected zone, thus keeping the zone small in the welded part.

In the following example, the mechanical properties of joints made by friction welding were superior to those of joints made by flash welding.

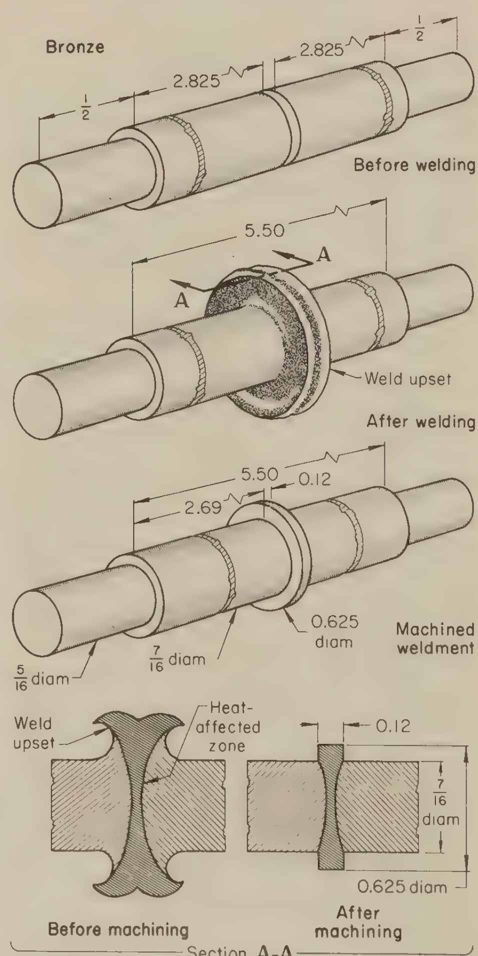
Example 452. Comparison of Properties of Joints Made by Flash Welding and by Friction Welding (Table 1)

A 1026 steel shaft 0.750 in. in diameter was joined to the stub shaft of a worm gear made of 5120 steel by conventional friction welding and by flash welding. Tension tests, rotating-beam fatigue tests and reversed-torsion fatigue tests were made on the weldments. The results of these tests are given in Table 1.

Examination of the microstructures of the welded joints showed a much narrower heat-affected zone and a finer grain structure in the friction welded joint than in the flash welded joint. The friction welded part had a higher tensile strength than the flash welded part.

For flash welding, the shaft had a sheared end and the stub shaft on the worm gear had a specially tapered section that reduced the flashing contact diameter from 0.750 in. to 0.375 in. This tapered section was flashed off during welding. For friction welding, the end of the shaft was used as-sheared but the end of the stub shaft on the worm gear was machined flat. Thus, the need for tapering the end was eliminated by changing from flash welding to friction welding.

In both methods, the worm gear was carburized and hardened before welding, but the stub shaft was flash copper plated,



Work-metal and machining costs were reduced substantially when friction welding replaced machining from bar stock. In the improved method, the center flange was machined from the upset produced by friction welding.

Fig. 3. Friction welded bronze valve stem (Example 451b)

Table 1. Comparison of Properties of Flash and Friction Welded Joints Made Between 1026 and 5120 Steel Bars (Example 452)

Test or property	Flash welding	Friction welding
Tensile strength	70,000 psi	75,000 psi
Bending fatigue time, minutes	32	180
Torsional fatigue time, cycles	1,000,000 (a)	4,000,000 (b)
Metal lost, in. (c)	0.75	0.25

(a) Cycles to failure. (b) Cycles without failure. (c) Axial shortening of bars during welding.

or covered with a tight-fitting cup, to prevent it from being carburized. Thus, the weld areas and the heat-affected zones produced by both welding methods had essentially the same hardness. No heat treatment was needed after welding, because both steels had low carbon contents (although one was a low-alloy steel); the as-welded hardness was acceptable in both the shallow heat-affected zone made by friction welding and in the wider zone made by flash welding.

Line-voltage variations frequently caused a severe drop in the flow of current to the flash welding machine, which resulted in a cold weld. Line-voltage regulators were needed to stabilize the current and shut off the power when the voltage dropped below a predetermined level. In friction welding, line-voltage fluctuations had little effect on the amount of frictional energy produced and voltage regulators were not needed.

The scrap rate for flash welding ranged from 3 to 6%, which was attributed to equipment maintenance, line-voltage variations, and defective components. In friction welding, scrap rate was less than 1%.

Because there is no spatter of weld flash during friction welding, the time required to clean the machines was reduced from 18 hours to less than 5 hours per week. The increased productivity that resulted from less downtime and higher production rate made it possible to use two friction welding instead of five flash welding machines.

Sections Welded. In friction welding, the joint face of at least one of the workpieces must be essentially round. The rotating workpiece should be somewhat concentric in shape because it revolves at a relatively high speed. Workpieces that are not round, such as hexagon-shape workpieces, have been friction welded successfully, but the resulting weld upset is rough, asymmetrical, and difficult to remove without damaging the welded assembly. For a few special applications, welding machines have been modified so that the spindle stops at the same place each time, thus making it possible for workpieces to be oriented to each other.

Solid bars of 1018 steel from ¼ to 4 in. in diameter can be friction welded in the available welding machines. Welding of larger diameters, although feasible, is limited by machine cost.

Wire and tubing of like and unlike metals 1 to 2.5 mm in diameter have been friction welded in special machines to plates 0.2 to 2 mm thick. Wires of unlike metals 1.5 to 2 mm in diameter have been joined.

Tubular sections can be much larger in diameter than the rated capacity of the welding machine for solid bars, and the maximum weldable tube diameter depends primarily on wall thickness. For example, a machine capable of welding a 4-in.-diam 1018 steel bar can weld a 1018 steel tube 30 in. in diameter with a 3⁄16-in.-thick wall. The maximum diameter decreases to about 7½ in. when the wall thickness is 1 in.

The size of section that can be friction welded depends somewhat on the distance the plastic metal must travel to be extruded from the weld interface. Metal in solid bars must travel outward from the center of the bar; metal in tubes can travel both inward and outward from the center of the wall.

Metals Welded

Friction welding can be used to join almost any metal that can be forged and that is not a good dry-bearing metal. The alloying elements that provide dry lubrication (or do not seize under normal operating conditions when without grease or other lubricants) prevent the interfaces from being heated to welding temperature by friction. Metals that contain free-machining additives are likely to be hot short and are generally unsatisfactory for welding.

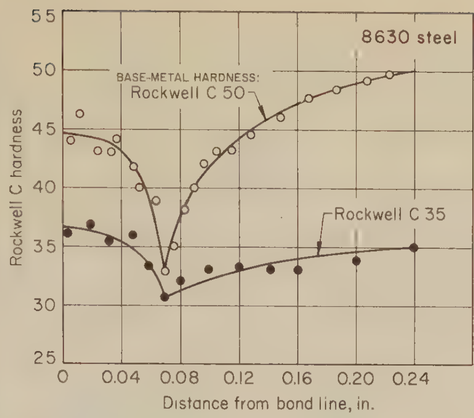
Many similar and dissimilar metal combinations can be friction welded, and in most combinations a sound metallurgical bond is formed. In some combinations, the bond is not as strong as the base metal, and postweld heat treatment may be needed to develop full weld-zone strength in alloy steels and hardenable stainless steels.

Carbon and alloy steels are relatively easy to friction weld. Low-carbon and medium-carbon steels can be welded under a wide range of welding conditions. High-carbon and alloy steels are easily joined but the welding conditions must be controlled within narrower ranges than are permissible for welding low-carbon steels, and the axial pressure must be increased to compensate for lower forgeability.

High speed tool steel can be welded to carbon and alloy steel shanks for making drills, reamers and other cutting tools. Steel balls made of 52100 steel, which is normally difficult to weld, are welded to one or both ends of carbon steel rods to make linkage rods. Frequently the rods are made of 1045 steel and one end is induction hardened before the 52100 steel ball is welded to the opposite end. The weldments are tempered after welding.

Free-machining steels, except those having a high sulfur and low manganese content, can be welded, but the free-machining elements result in undesirable directional properties in the weld zone. Friction welds in free-machining steels have fatigue strength less than 80% that of the base metal and should not be used in applications where high stresses are involved and high fatigue strength is required. Friction welding of free-machining steels should be limited to those with 0.08 to 0.13% sulfur, lead or tellurium. For example, 1141 steel is welded satisfactorily, but 1144 is not.

Heat treated steels can be friction welded with only localized changes in hardness because the heating is confined to a very narrow zone. Also, the rapid quenching restores hardness to the weld zone. For instance, as shown in Fig. 4, when 8630 steel bars were hardened to Rockwell C 35 or C 50 and then were friction welded, the minimum hardnesses (Rockwell C 33 for the Rockwell C 50 steel; Rockwell C 31 for the Rockwell C 35 steel) occurred at about 0.065 in. from the bond line; the heat-affected zone extended about 0.24 in. into the base metal. In welding hardenable steel, the weld upset usually reaches a high hardness because of rapid quenching. Therefore, the weld upset usually must be removed by grinding, or by machining after annealing. In some applications, the upset is removed by hot shearing before it has cooled from the welding temperature to the M_s temperature.



Bars for upper curve postweld tempered at 400 F; those for lower curve, at 1000 F.

Fig. 4. Relation of metal hardness in the heat-affected zone to distance from the bond line after friction welding 8630 steel bars having hardnesses of Rockwell C 35 and C 50

Sintered metals are further compacted during friction welding and have a wrought structure in the weld zone. The joint usually is stronger than the base metal.

The results of friction welding steel forgings and steel castings are about the same as those of friction welding steel bars of similar composition.

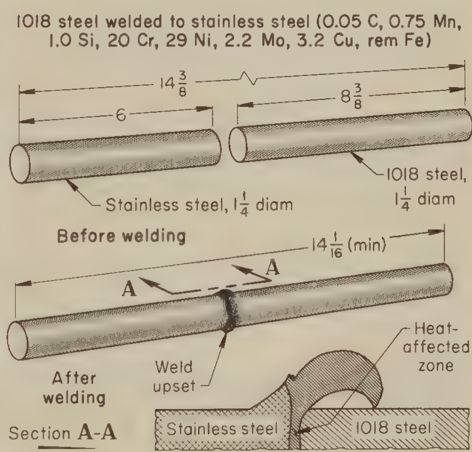
Stainless steels are comparatively easy to friction weld, and good weld properties can be obtained under a wide range of welding conditions. The heat treatable stainless steels are sensitive to heat and pressure and, for good weld properties, require postweld heat treatment in the heat-affected zone. An important application of friction welding of stainless steel is the production of bimetal shafts that are exposed to a corrosive atmosphere or to wear in service. To provide the correct type of resistance where needed, to reduce work-metal cost, or to increase machinability, an alloy that will withstand a corrosive atmosphere can be joined to a metal that is less expensive and easier to machine, as in the example that follows.

Example 453. Comparison of Costs for Making a Pump Shaft by Machining From One Piece of Stainless Steel and by Machining an Inertia Weldment (Fig. 5)

The cost of making the pump shaft shown in Fig. 5 from one piece of stainless steel (0.05 C, 0.75 Mn, 1.0 Si, 20 Cr, 29 Ni, 2.2 Mo, 3.2 Cu, rem Fe) was compared with the cost of making the shaft by inertia welding a bar made of the same stainless steel to a bar made of 1018 steel. In making the bimetal shaft, most of the machining was done on the 1018 steel, which was less expensive and easier to machine than the stainless steel.

When the shaft was made from the two metals instead of from stainless steel only, material cost was reduced by 45% and machining cost was reduced by 10%. Metallographic examination of the inertia welded joint showed good fusion, and when the shafts were field tested in pumps running at 3500 rpm, no failures were reported.

Before welding, the ends of both bars were ground to remove any mill scale. After welding, weld upset was removed as the shaft was machined to size. In order to produce good welds, leaded low-carbon steel was not used. The conditions for inertia welding and the production rates are given in the table that accompanies Fig. 5.



Conditions for Inertia Welding

Flywheel moment of inertia	50 lb-ft^2
Spindle speed	3150 rpm
Weld energy(a)	84,000 ft-lb
Axial force	60,000 lb
Heat-and-weld time	2 to 4 sec
Weld area	1.23 sq in.
Metal lost, max(b)	5/16 in.
Production rate:	
Manual	120 welds per hour
Automatic	360 welds per hour

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Fig. 5. Pump shaft that was made by machining an inertia weldment of stainless steel and 1018 steel, instead of by machining from stainless steel only, to reduce costs (Example 453)

Cast iron in any form — gray, ductile or malleable — has not been friction welded satisfactorily in production. (Joining of ductile iron to steel in laboratories has been reported.) Free graphite gathers at the interface and acts as a lubricant, which limits friction heating. Also, these materials are not forgeable, which is a general requirement for friction welding.

Nonferrous Metals and Alloys. Aluminum alloys are friction welded to similar and dissimilar aluminum alloys, copper alloys to similar and dissimilar copper alloys, and aluminum alloys to copper alloys. Most applications of friction welding these metals are in joining aluminum and copper alloys to steel, although problems are presented by high thermal conductivity, large differences in forging temperatures, and the formation of brittle intermetallic compounds.

Joints between aluminum alloy 6061 and copper have a tensile strength near that of the copper. Joints between aluminum alloy 1100 and stainless steel have a strength near that of the aluminum alloy. Friction welding of other aluminum alloys may develop a joint strength of only 60 to 70% that of the weaker base metal. Even though these

joints are relatively weak, they are useful for pressure sealing and for joining assemblies that require good electrical and thermal conductivity, rather than high strength.

Titanium, titanium alloys, zirconium alloys and magnesium alloys can be friction welded to themselves.

Most nickel-base and cobalt-base alloys, including the heat-resisting alloys, are easily welded to themselves and to alloy steels. The nickel-base alloy GMR-235 can be welded to 1040 steel, Inconel 718 to Inconel 713C, and Inconel 713C to 8630 steel in producing jet-engine parts that require high-strength bonds.

The refractory metals — tungsten, molybdenum, columbium and tantalum — can be welded to themselves. Friction welds between molybdenum rods are ductile enough to withstand substantial reduction by wire drawing.

Conventional Friction Welding

Conventional friction welding requires a machine resembling an engine lathe equipped with an efficient spindle-braking system, a means of applying and controlling axial pressure and a weld-cycle timer and control. The equipment is simple in principle, but the machines are complex when big enough to weld large workpieces.

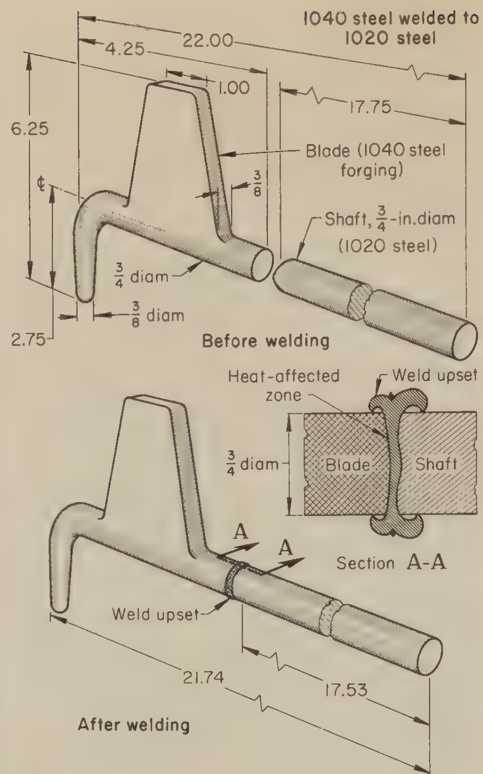
Principle of Operation. The workpiece to be rotated is clamped in the spindle chuck, and the spindle is brought to a predetermined speed. The nonrotating component is clamped in a chuck or fixture mounted to a hydraulically actuated tailstock slide. To heat the workpieces to welding temperature, the tailstock slide is advanced to bring the workpieces in contact under a constant or gradually increasing axial pressure. When the workpieces are at, or slightly above, the welding temperature, the spindle brake is applied, which suddenly stops the spindle rotation. Simultaneously, the tailstock pressure is increased to complete the weld.

The spindle speed, axial pressure and length of time the pressure is applied for a given weldment depend on (*a*) the cross-sectional area of the workpieces to be welded; (*b*) the melting point and thermal conductivity of the work metal; and (*c*) the metallurgical changes that occur during the heating cycle, particularly when dissimilar metals are being welded.

Process variables to be controlled are rotational speed, initial (heating) pressure, length of time that heating pressure is applied, and welding pressure. The time needed to stop the spindle can affect the temperature to which the workpieces are heated, timing of application of the welding pressure, and weld properties.

Rotational speed, or peripheral velocity, is the least sensitive process variable and can be varied over a wide range if heating time and pressure are properly adjusted. However, heating time must be limited to prevent excessive depth of heating. The peripheral velocity recommended for welding most low-carbon, medium-carbon, and high-carbon steels is 400 to 1400 sfm.

Heating pressures used for welding low-carbon and low-alloy steels are from 3000 to 20,000 psi. Welding pressures for these steels are from 5000 to 25,000 psi. Usually, the welding pressure is higher than the heating pressure, but sometimes they are nearly the same.



Item	Welding process Flash	Friction
Cost Comparison		
Production, parts per hour	240	300
Steel savings(a)	...	\$5500
Scrap loss(b)	6 to 7%	½ to 1%
Forging scrap loss	3.5%	1.5%
Fixture maintenance(c)	\$1830	\$1050

(a) For each 100,000 units. (b) From misalignment, burns and other causes. (c) Cost per year.

Fig. 6. Shutdown-control shaft that was made by joining a steel forging to a steel shaft at lower cost by friction welding than by flash welding (Example 454)

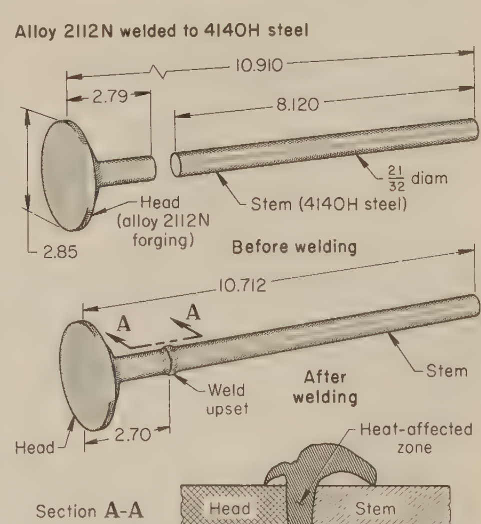


Fig. 7. Diesel-engine exhaust valve that was made by friction welding a heat-resisting alloy to a low-alloy steel (Example 455)

For medium-carbon and high-carbon steels, heating pressures are from 10,000 to 30,000 psi, and welding pressures are from 15,000 to 60,000 psi. Lower heating pressures are sometimes used for large workpieces so that the power requirements do not exceed the capacity of the welding machine.

Heating time varies with the heating pressure, the carbon and alloy content of the steel, and the diameter of the workpiece. Usually, heating time is determined by trial.

The spindle should be stopped rapidly to keep the weld from twisting or tearing. For a workpiece less than ½ in. in diameter, stopping time should be within 1½ sec; a 3-in.-diam bar should be stopped within 3 sec.

Examples of Practice. Only minor alterations in design are needed to adapt to friction welding a workpiece that previously was butt welded by other processes. Generally, in friction welding less metal is lost during heating and upsetting than in flash welding, and it is not necessary, as it is in flash welding, to machine the interface so that heating will start at the center of the workpiece section. Where allowances are made in the size of a forging for differences in metal lost and for welding in the as-forged condition, forging costs can be reduced, as in the following example.

Example 454. Comparison of Friction Welding and Flash Welding of Shutdown-Control Shafts (Fig. 6)

The shutdown-control shaft for a textile loom was made by butt welding a ¾-in.-diam 1020 steel shaft to a forged 1040 steel blade, as shown in Fig. 6. In service, these shafts received severe impact loading and thus required excellent weld quality. Satisfactory joints were made by both flash welding and conventional friction welding, but scrap loss was lower with friction welding than with flash welding because of better accuracy of alignment.

For friction welding, the stub shaft on the forging was ¾ in. shorter than that needed for flash welding because no metal was lost during flashing and the forging was not machined before welding. The over-all length of the control shaft was not held to close tolerances, and therefore, the stub shaft on the blade was friction welded in the as-forged condition. The stub shaft was machined before flash welding so that flashing would start at the center. The shorter forging used for friction welding was easier to produce and required less material. The 1020 steel shaft was used as-sheared for both processes.

The only machining required on the friction welded shaft was removal of the weld upset by grinding. This finished surface served as a bearing journal for the blade end of the shaft.

A comparison of costs for flash and friction welding of the shafts is given in the table that accompanies Fig. 6.

Workpieces made of dissimilar metals are frequently used in order to minimize costs while still providing, where needed, a work metal that meets the necessary service requirements. Many corrosion-resisting and heat-resisting alloys are welded to less expensive alloys to reduce material and machining costs, or to provide a wear-resistant surface. This was done in Example 453 (in which a high-alloy stainless steel was friction welded to 1018 steel), and in the exhaust-valve application described in the example that follows.

Example 455. Production of Diesel-Engine Exhaust Valves by Friction Welding Dissimilar Alloys (Fig. 7)

A large exhaust valve for a diesel engine, shown in Fig. 7, was made by conventional friction welding a head made of a heat-resisting alloy to a low-alloy steel stem. This permitted using the more expensive (heat-resisting) alloy only where required.

The head was forged from alloy 2112N (a 21Cr-12Ni austenitic iron-base alloy used for exhaust valves), and the stem was made of 4140H steel $^{21}/_{32}$ in. in diameter. The initial weld area was 0.34 sq in. Overall length of the part after joining by friction welding was 10.712 in.

A 25-hp friction welding machine was used, although the peak requirement was only 5 hp.

In operation, the valve head was clamped in an air-actuated fixture mounted in the tailstock, and the stem in an air-actuated chuck attached to the machine spindle.

The machine cycle was started, and the spindle was rapidly accelerated to 2700 rpm as the tailstock advanced to bring the workpieces into contact. The pressure of contact initiated a signal in the control circuit that began cycle timing and started a gradual increase in axial pressure by a slope-control unit.

The pressure, applied through the tailstock by two hydraulic cylinders, was smoothly increased to 11,000 psi (about 3740 lb) in 4 sec. The pressure level was maintained for an additional 4 sec, during which time the workpieces were heated to welding temperature.

At the end of the 4-sec heating period, the braking system quickly stopped spindle rotation, and a welding pressure of 32,000 psi (about 10,900 lb) was applied. The resulting weld had a good metallurgical bond that was free of oxides, cast metal structure, porosity, inclusions and other defects. Total axial shortening of the workpieces during welding was 0.195 to 0.200 in.

The weld upset was removed in an automatic lathe prior to heat treating of the valve. After heat treatment, the stem was ground to finished diameter.

The production rate, with an unskilled operator, was 190 to 200 pieces per hour. The total input energy per weld was 6900 watt-sec with a peak power draw of 5 hp, including all losses. The cost per weld, including removal of the weld upset, was less than $0.05. The welding machine cost $20,000, and the semiautomatic loading and unloading equipment cost $3000 (1967).

Inertia Welding

Inertia welding makes use of the kinetic energy of a freely rotating flywheel for all of the heating required to produce a weld.

Welding Machine. The machine is constructed with a horizontal bed and overhead tie bars to contain the axial-pressure and torque reactions and to ensure accurate spindle-to-bed alignment. The spindle is driven by a hydrostatic motor through a change-gear transmission. A hydraulically actuated tailstock retracts on adjustable ways for loading and unloading. A self-centering vise can be attached to the tailstock for clamping cylindrical parts, and fixtures are used for holding asymmetrical parts for which the vise is not suitable. The spindle has a means for mounting a collet chuck, and a draw bar is used for opening and closing the collet.

Flywheel size (moment of inertia of the flywheel or spindle) is adjusted by adding or removing flywheel disks. The spindle speed and axial pressure are adjusted by dials on the control panel.

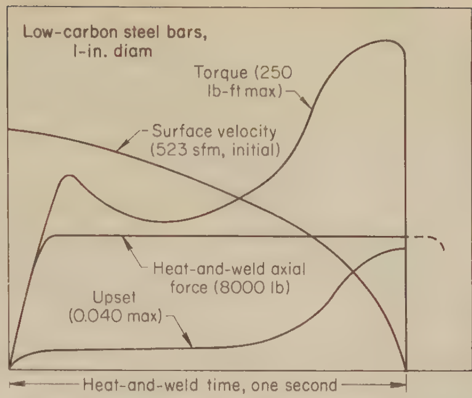


Fig. 8. Variation of surface velocity, torque, axial force and weld upset in a one-second heat-and-weld time in inertia welding

Principle of Operation. In inertia welding, as in conventional friction welding, one workpiece is clamped in a nonrotating vise or fixture and the other workpiece is clamped in a chuck mounted to a rotating spindle.

The drive motor accelerates the rotation of the flywheel-spindle assembly to a predetermined speed, and then the rotating drive power is shut off. The surfaces to be welded are brought together and the kinetic energy of the freely rotating flywheel is rapidly converted to heat at the weld interface as axial pressure is applied. Once the axial pressure, flywheel moment of inertia, and spindle speed have been established for a given workpiece, uniform welds are produced repetitively.

Two characteristics of inertia welding — continuously decreasing surface velocity of the workpiece and continuously changing torque at the weld interface — are illustrated in Fig. 8. Surface velocity begins at some initial value and decreases along an essentially parabolic curve to zero, at which time the weld is completed. Heating and welding time is usually 0.2 to 4 sec. Torque has a peak value of short duration early in the cycle, gradually decreases, and then increases until the velocity has decreased to the value at which welding begins, at which time torque rises sharply. This high torque is accompanied by forging in the weld zone, and is responsible for much of the upsetting. The high-torque phase, present only in inertia welding, refines the grain structure and expels any oxides at the weld interface. The gradually decreasing and increasing part of the torque curve is essential to the formation of good welds. The second (low-torque) phase generally will not develop if initial velocity is too low. Figure 8 is typical for inertia welding of 1-in.-diam low-carbon steel bars.

Other differences between inertia welding and conventional friction welding are input power at the weld interface and heating time. The power needed for the weld itself is not of concern in inertia welding, because whatever power is required can always be supplied by deceleration of the flywheel at the required rate. In conventional friction welding, power is limited by the size of the drive motor.

The high power used in inertia welding is a result of a relatively high, rapidly applied axial pressure. Power demands in conventional friction welding are controlled and limited to motor capacity by applying the axial pressure slowly; usually 2 to 4 seconds elapse before the full pressure is applied. The lower heating rates of conventional friction welding require more energy because much of the heat is conducted away from the weld interface. By rapid application of small amounts of energy, inertia welding produces narrower heat-affected zones than those produced in conventional friction welding.

In inertia welding, intense hot working of the weld zone in conjunction with rapid cooling immediately after hot working results in a very small grain size in the as-welded condition. Subsequent heat treatment will restore the grains to their normal size.

Process Variables. Three variables control the characteristics of an inertia weld: initial peripheral velocity of the rotating workpiece, axial pressure, and flywheel size (moment of inertia).

Table 2. Conditions for Inertia Welding 1-In.-Diam Bars in Combinations of Similar and Dissimilar Metals

Work metal	Welding conditions: Spindle speed, rpm	Axial force, lb	Flywheel size, lb-ft² (a)	Resultant weld conditions: Weld energy, ft-lb	Metal lost, in. (b)	Total time, sec (c)
Metals Welded to Themselves						
1018 steel	4600	12,000	6.7	24,000	0.10	2.0
1045 steel	4600	14,000	7.8	28,000	0.10	2.0
4140 steel	4600	15,000	8.3	30,000	0.10	2.0
Inconel 718	1500	50,000	130.0	50,000	0.15	3.0
Maraging steel	3000	20,000	20.0	30,000	0.10	2.5
Type 410 stainless steel	3000	18,000	20.0	30,000	0.10	2.5
Type 302 stainless steel	3500	18,000	14.0	30,000	0.10	2.5
Copper, commercially pure	8000	5,000	1.0	10,000	0.15	0.5
Copper alloy 260 (cartridge brass, 70%)	7000	5,000	1.2	10,000	0.15	0.7
Titanium alloy Ti-6Al-4V	6000	8,000	1.7	16,000	0.10	2.0
Aluminum alloy 1100	5700	6,000	2.7	15,000	0.15	1.0
Aluminum alloy 6061	5700	7,000	3.0	17,000	0.15	1.0
Dissimilar-Metal Combinations						
Copper to 1018 steel	8000	5,000	1.4	15,000	0.15	1.0
M2 tool steel to 1045 steel	3000	40,000	27.0	40,000	0.10	3.0
Nickel alloy 718 to 1045 steel	1500	40,000	130.0	50,000	0.15	2.5
Type 302 stainless to 1020 steel	3000	18,000	20.0	30,000	0.10	2.5
Sintered high-carbon steel to 1018	4600	12,000	8.3	30,000	0.10	2.5
Aluminum 6061 to type 302 stainless	5500	5000 & 15,000 (d)	3.9	20,000	0.20	3.0
Copper to aluminum alloy 1100	2000	7,500	11.0	7,500	0.20	1.0

(a) Moment of inertia of the flywheel. (b) Total axial shortening of workpieces during welding. (c) Includes heat time and weld time. (d) The 5000-lb force is applied during the heating stage of the weld; force is increased to 15,000 lb near the end of the weld.

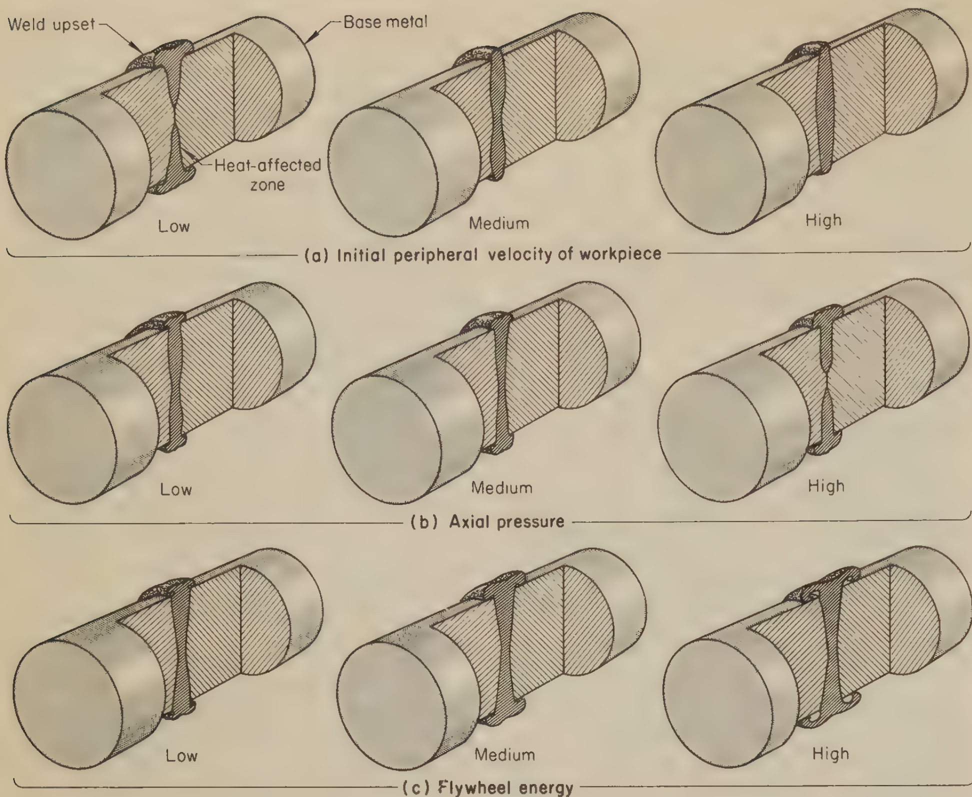
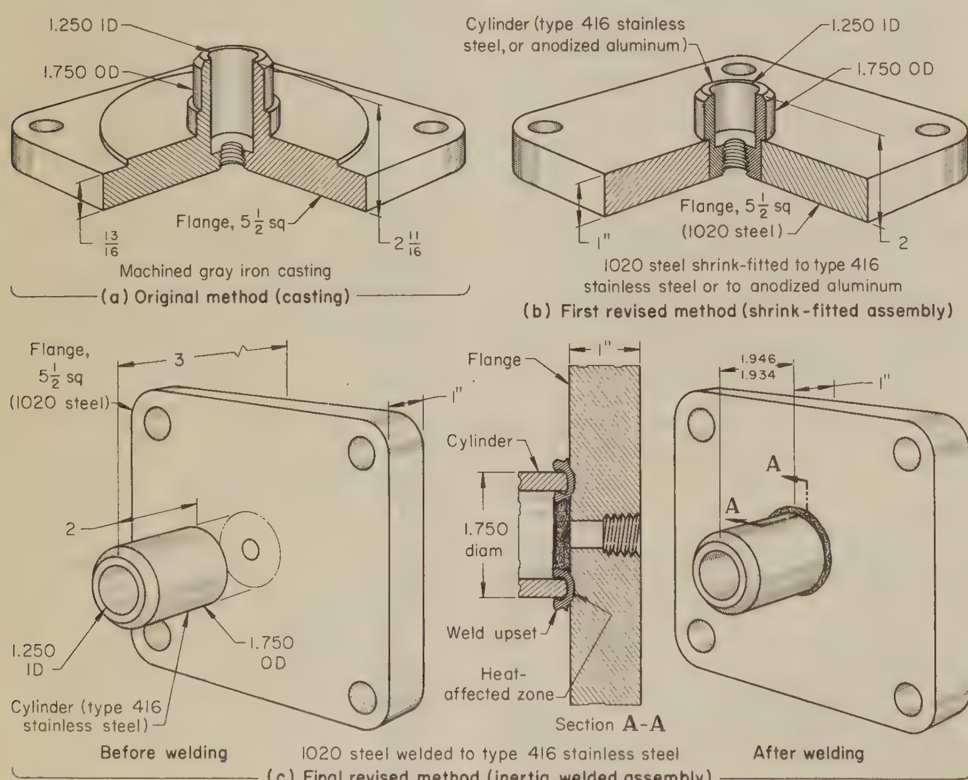


Fig. 9. Effect of low, medium and high levels of the three welding variables on depth and uniformity of heating, and on size and shape of the weld upset, in inertia welding of steel



Conditions for Inertia Welding

Machine capacity:		Spindle speed	3900 rpm
Part diameter	0.43 to 1.50 in.	Weld energy(a)	51,800 ft-lb
Spindle speed	8000 rpm max	Axial force	35,000 lb
Axial force	45,000 lb max	Weld area	1.18 sq in.
Flywheel moment of inertia	20 lb-ft²	Metal lost(b)	0.060 ± 0.006 in.

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Fig. 10. Suction-valve cover that was produced by three different processes, using the designs shown. Inertia welding produced the highest-quality part at lowest cost. (Example 456)

For each weld, the minimum energy input required is provided by using the proper combination of flywheel size and spindle speed. Additional energy may be needed if the surfaces to be welded are rough or out of square with the axis of rotation. Very high energy input causes excessive loss of metal, but generally does not affect the strength or quality of the weld.

Table 2 gives representative conditions for inertia welding of 1-in.-diam bars of various metals and alloys, in similar and dissimilar combinations.

Peripheral Velocity of Workpiece. For each combination of work metals, there is a range of peripheral velocity that produces the best weld properties. For welding steel to steel, the recommended initial peripheral velocity of the workpiece ranges from 500 to 1500 sfm; however, welds can be made at velocities as low as 275 sfm. As illustrated in Fig. 9(a), low velocities (less than 300 sfm) can reduce center heating and produce rough, uneven weld upset. At medium velocities (300 to 900 sfm), the heating pattern in steel has an hourglass shape at the lower value and gradually flattens as the upper velocity is approached. The heating pattern is essentially flat and uniformly thick across the workpiece at velocities of 900 to 1200 sfm. At high initial velocities (above 1200 sfm), the weld becomes rounded and is thicker at the center than at the periphery.

Spindle speeds in revolutions per minute for inertia welding 1-in.-diam bars of various metals and alloys are given in Table 2. (For speed conversions — sfm to rpm for many diameters — see the inside back cover of Volume 3 of this Handbook.) The relationship of total time and weld upset to bar diameter is approximately linear.

Axial Pressure. The effect of varying the axial pressure is similar but opposite to the effect of varying the velocity. As Fig. 9(b) shows, welds made at low axial pressure resemble welds made at medium velocity, in regard to formation of weld upset and heat-affected zones. Use of excessive pressure produces a weld that is poor at the center and has a large amount of weld upset, similar to a weld made at a low velocity.

The axial force (in pounds) for welding 1-in.-diam bars is given in Table 2. Axial pressure (in psi) varies as a function of the square root of workpiece diameter. For instance, a 2-in.-diam bar uses 1.414 times the axial pressure needed for a 1-in.-diam bar.

Effect of Flywheel Energy. The flywheel moment of inertia is selected to produce the desired amount of kinetic energy and the desired amount of forging. Forging results from the characteristic increase in torque (see Fig. 8) that occurs at the weld interface as the flywheel slows and comes to rest. This increased torque, in combination with the axial pressure, produces forging as depicted by the upset curve in Fig. 8. Because forging begins at some critical velocity (about 200 sfm for low-carbon steel), the amount of forging depends on the amount of energy remaining in the flywheel, which is a linear function of the flywheel moment of inertia. Large, low-speed flywheels produce greater forging than small,

high-speed flywheels even though they contain the same amount of kinetic energy. Although low, medium and high amounts of flywheel energy produce similar heating patterns, the amount of energy greatly affects the size and shape of the weld upset, as shown in Fig. 9(c).

Examples of Practice. Inertia welding is used in the manufacture of bimetal exhaust valves for internal-combustion engines, bimetal shafts for pumps, and cluster and ring gears for automotive and aircraft applications. The process has been incorporated into the redesign of many parts in order to reduce costs or improve service life, as in the following two examples. Other applications of inertia welding are described in the section on Friction Welding vs Other Processes, beginning on page 516.

In the example that follows, to produce corrosion-resistant parts at low cost, inertia welding was selected over casting or shrink-fit assembly.

Example 456. Use of Inertia Welding Instead of Casting or Shrink-Fit Assembly (Fig. 10)

A high-production part, consisting essentially of a 1¼-in.-ID cylinder with a bolting flange, served as a suction-valve cover. The manufacturing process and design of the part evolved through three successive stages as shown in Fig. 10. The first stage was a one-piece casting (Fig. 10a); the second, a shrink-fitted assembly (Fig. 10b); and the third, the inertia welded assembly shown in Fig. 10(c). The slight differences among the three designs are the results of changes in the design of the mating piece. The inertia welded component was used as-welded, without removing weld upset from either the inner or the outer surface of the cylinder.

Originally, the part was machined from a gray iron casting as shown in Fig. 10(a). Some difficulty was experienced in obtaining the desired finish on the inner surface of the cylinder, but the most serious problem was rusting of the inside of the cylinder. Attempts were made to improve corrosion resistance by burnishing the cylinder wall, and then plating with cadmium, zinc or tin, or phosphate coating. Although phosphate coatings were best on the cast iron surface, none of these coatings proved satisfactory in service.

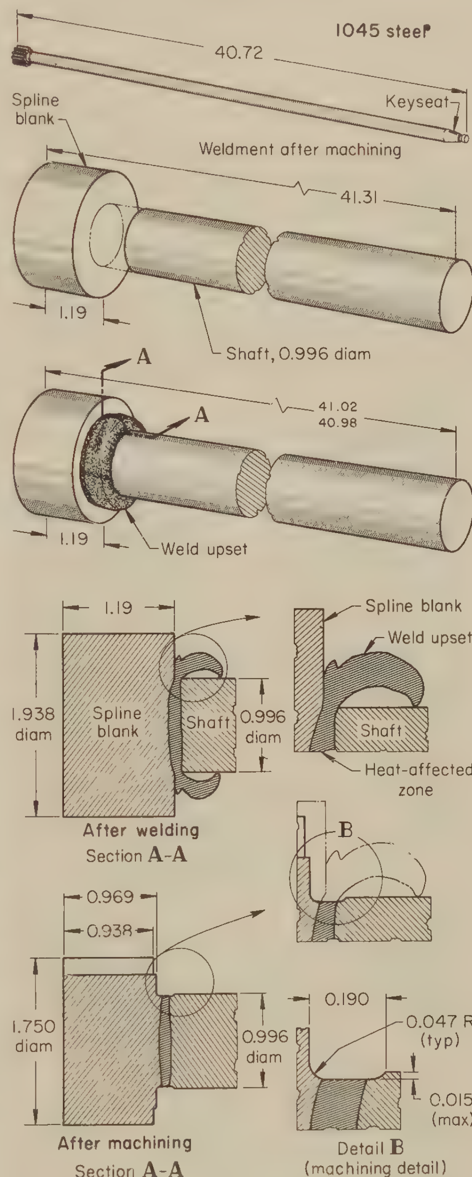
The second method consisted of using for the flange a low-carbon steel plate that was bored to accept a shrink-fitted cylinder (Fig. 10b). Cylinders were made of anodized aluminum alloy or of stainless steel. When the anodized aluminum alloy was used, the cost per part was slightly higher than that of the gray iron casting. Cylinders made of type 416 stainless steel gave excellent results, but cost considerably more than the castings.

In the final design, shown in Fig. 10(c), inertia welding was used to join a type 416 stainless steel tube to a 1020 steel plate. Valve covers made by this method cost 15% less than the original cast iron covers and the corrosion and surface-finish problems were eliminated.

For inertia welding, flanges were gas cut from 1020 steel plate, and the cylinders were saw cut from type 416 stainless steel tubing. Both components were finish machined and the joint surfaces were cleaned carefully before welding.

Conditions for friction welding are given in the table with Fig. 10. With these settings, an upset of 0.060 ± 0.006 in. was a good indication of an acceptable weld. Part specifications required that a 100-psi pressure test be applied to 5% of the weldments, and that 1% of the weldments be examined for weld configuration by sectioning. The test samples were selected on a random basis. Under these conditions, the rejection rate was less than 0.3%, and most rejections were caused by defects in the base metal rather than in the weld.

The manufacture of a long, slender shaft with a spline on one end is described in the example that follows. Use of inertia welding permitted joining a ground and polished steel shaft to another steel part without damaging the polished surface. Changing from forging to inertia welding reduced the over-all cost and eliminated nine manufacturing operations.



Conditions for Inertia Welding(a)

Flywheel moment of inertia	150 lb-ft²
Spindle speed	1850 rpm
Weld energy(b)	87,500 ft-lb
Axial force	21,000 lb
Weld area	0.78 sq in.
Metal lost(c)	0.31 ± 0.02 in.
Production rate	70 welds per hour

(a) In this application, lower-than-normal spindle speeds and larger-than-normal flywheels were used for convenience in changeover from one workpiece to another. (b) Calculated from flywheel size (moment of inertia) and spindle speed. (c) Total axial shortening of the workpieces during welding.

Fig. 11. Drive shaft for which change from forging to inertia welding reduced costs by $12.17 (Example 457)

Example 457. Change From Forging to Inertia Welding To Reduce the Cost of Producing a Long, Slender Shaft (Fig. 11)

The long, slender power-control drive shaft shown in Fig. 11 originally was made from a 1045 steel forging, but was severely warped during forging and heat treating. Nineteen manufacturing operations were needed to complete the forged shaft, including hardening and tempering of the forging to Rockwell C 23 to 30, cleaning by shot blasting, three straightening operations and ten machining operations.

The number of manufacturing operations was reduced to ten when forging was replaced by inertia welding. A spline blank of 1045 steel 1.938 in. in diameter by 1.19 in. long was inertia welded to a 1045 steel shaft 40.12 in. long (see Fig. 11). The shaft had a hardness of Rockwell C 27 and, before welding, was ground and polished to 0.996 in. in diameter. The jaws for holding the shaft were designed so as not to damage the ground and polished surface.

Hardening, tempering, shot blasting, straightening and three grinding operations were eliminated, and the cost of making each shaft was reduced by $12.17, when forging was replaced by inertia welding. Three operations — hardening a bearing surface, deburring, and washing — were included in both manufacturing sequences.

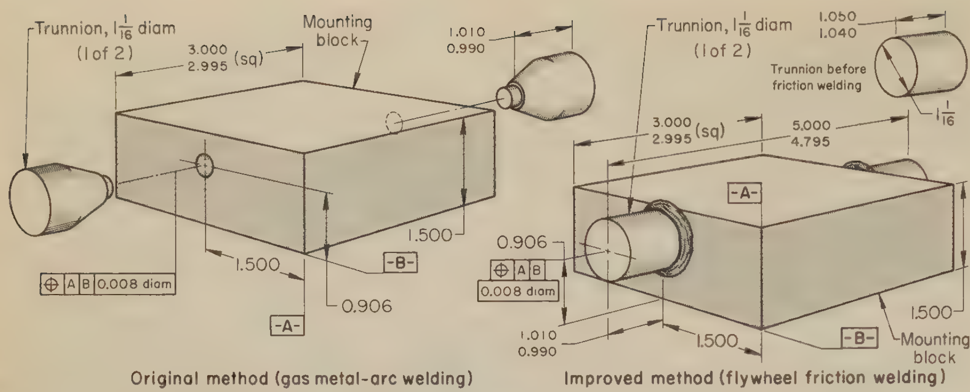
Machining of the spline end of the weldment included removing the weld upset and relieving the area to a minimum diameter of 0.966 in. and to a width of 0.19 in., which eliminated a possible stress raiser. A taper 1.375 in. long, a seat for a Woodruff key, and ⅝-11 threads were machined on the other end of the shaft.

Conditions for inertia welding are given in the table with Fig. 11. These conditions were selected to produce a weld upset of 0.31 ± 0.02 in., which was greater than usual, so that the upset could be machined in the as-welded condition. Failure of the shaft during fatigue testing occurred at the keyseat, not in the weld.

Flywheel Friction Welding

Flywheel friction welding is done with a machine in which mechanical energy is stored in, and released by, a flywheel in amounts predetermined and gaged by flywheel speed. The amount of energy released by the flywheel is determined by its speed when axial pressure is first applied, and by the speed at which the clutch disengages the spindle from the motor. (For additional description of the mechanics of flywheel friction welding, see "Welding Methods" on page 507.)

In operation, one workpiece is clamped in a collet chuck mounted to the spindle and the clutch is engaged, which causes the workpiece to be rotated at a predetermined speed. The mating workpiece is clamped in the tailstock and then brought in contact with the rotating workpiece, and pressure is applied to heat the workpieces. At a predetermined time or spindle speed, the clutch is disengaged and a welding pressure is applied to stop rotation and complete the weld. After the flywheel is disengaged, the heating pressure can be continued or the welding pressure can be applied immediately. Thus both kinetic and direct mechanical energy can be used to heat the workpieces to welding temperature, although the machine is designed with the intent that all heating be derived from the kinetic energy of the freely rotating flywheel, and none from direct mechanical energy.



Conditions for Flywheel Friction Welding	
Flywheel moment of inertia	40 lb-ft²
Spindle speed	1800 rpm
Weld energy(a)	21,800 ft-lb
Axial force	18,000 lb
Time per weld	1 sec
Time, floor to floor	30 sec
Metal lost (b)	0.045 ± 0.005 in.

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Operation	Gas metal-arc welding	Flywheel friction welding
Comparison of Costs per Mount		
Machine two trunnions	$0.90	$0.06
Drill two holes in block	0.12	...
Assemble trunnions to block	0.10	...
Weld	0.85	0.50
Total cost per mount	$1.97	$0.56
Saving per mount		$1.41

Fig. 12. Original and improved methods of welding trunnions to a mounting block to make a trunnion mount for air and hydraulic cylinders. Cost per mount was reduced by 71% when flywheel friction welding replaced gas metal-arc welding. (Example 458)

The variables in flywheel friction welding are rotational speed, flywheel size (moment of inertia), cutout speed and axial pressure. The effects of each variable (except cutout speed) on the weld are the same as in inertia welding. The continuous rotation of the drive-motor – flywheel assembly makes the weld energy almost immediately available as soon as the workpieces are loaded into the collets or fixtures.

In the example that follows, gas metal-arc welding was replaced by flywheel friction welding for joining trunnions to a mounting block. In both of the methods used to join the three components, the location of each trunnion was held to a close tolerance, to minimize the machining necessary to make the trunnions concentric.

Example 458. Joining of Trunnions to Mounting Blocks by Flywheel Friction Welding at Lower Cost Than by Gas Metal-Arc Welding (Fig. 12)

A trunnion mount (see Fig. 12) for air and hydraulic cylinders originally was made by gas metal-arc welding two trunnions to a mounting block. When the joining process was changed to flywheel friction welding, the total cost of making the mount was reduced by 71%.

In the original method, the trunnions were machined from bar stock and then gas metal-arc welded to a mounting block. Each trunnion had a locating boss and a weld chamfer. The block was drilled to accept the trunnions, which were pressed in, and then welded. After welding, the trunnions were machined concentric. Before welding, the blocks were broached square and parallel within 0.005 in. To minimize the machining necessary to make them concentric, the trunnions were held within 0.008 in. of true position. As shown in the table with Fig. 12, the cost of machining and arc welding the trunnions was $1.97 per block.

When the process was changed to flywheel friction welding, the trunnions were saw cut to 1.050 +0.000, −0.010 in. in length and the broached blocks were not drilled. The cost of cutting two trunnions to length and friction welding them to a block was $0.56.

The trunnions were held by a collet chuck mounted to the spindle of the flywheel friction welding machine and the mounting block was located and held in a fixture mounted to the tailstock. The length of each trunnion was held to 1.000 +0.000, −0.010 in., which eliminated the need for facing the ends after welding. Time for each weld was 1 second; floor-to-floor time for each piece was 30 seconds. Additional conditions for flywheel friction welding, and a comparison of costs for the two processes, are given in the table that accompanies Fig. 12.

Joint Design

The mechanics of friction welding restrict its use to flat and angular butt welds that are perpendicular to and concentric with the axis of rotation. Flat joints are the most common and can be classified as: (*a*) bar to bar, (*b*) bar to tube, (*c*) tube to tube, (*d*) bar to plate, and (*e*) tube to plate, as shown in Fig. 13. These classifications refer to the joint itself, and not to the shape of the parts. The joint used in making the rotor bodies described in Example 451 is classified as a bar-to-plate joint because a 0.62-in.-diam rod was joined to a 2-in.-diam rod. Friction welding the cluster gears in Example 463 illustrates a tube-to-plate joint on the OD of the gear and a tube-to-tube joint on the ID.

Joint surface conditions, such as surface finish, squareness and cleanness, are not critical for friction welding because the original abutting surfaces are rubbed off and extruded in the process. As-forged, sheared, gas-cut, abrasive-cut or sawed surfaces are acceptable, but extra heat is needed to remove irregularities and allow uniform heating to occur. Also, if the face of a workpiece is not perpendicular to the axis of rotation, forces are produced that can affect the concentricity of the components after welding.

Projections left by cutoff tools present no problem, and in some applications may even help to heat the center of the bar. However, center-drill holes must be avoided; when the upset metal compresses the air entrapped in a center-drill hole during upsetting, a weld defect usually occurs.

Heavy mill scale, thick chromium plating or a thin carburized or nitrided case acts as a bearing surface and cannot be extruded from the weld area. When deeply carburized workpieces are to be welded, the joint surface, and the adjacent surfaces, must either be machined before welding (or before hardening, if it precedes welding) to remove the carburized metal, or be copper plated or otherwise covered during the carburizing operation to prevent them from being carburized. In Example 463, the weld area was machined before hardening to remove the carburized metal. In Example 451, the end to be welded was copper plated before carburizing.

Tubular Welds. Tube-to-plate welds are not as strong as tube-to-tube welds, because rounding of the end of the tube during heating and upsetting reduces weld effectiveness. Fatigue life of a tube-to-plate weldment increases with removal of the sharp notch at the tube base before the part is put to use. On some metals, when heating is too slow, or when excessive weld energy is applied, the upset metal flows up and around the outside of the tube and forms, in effect, a tube within a tube.

On tubular welds, the upset is extruded equally toward the bore and to-

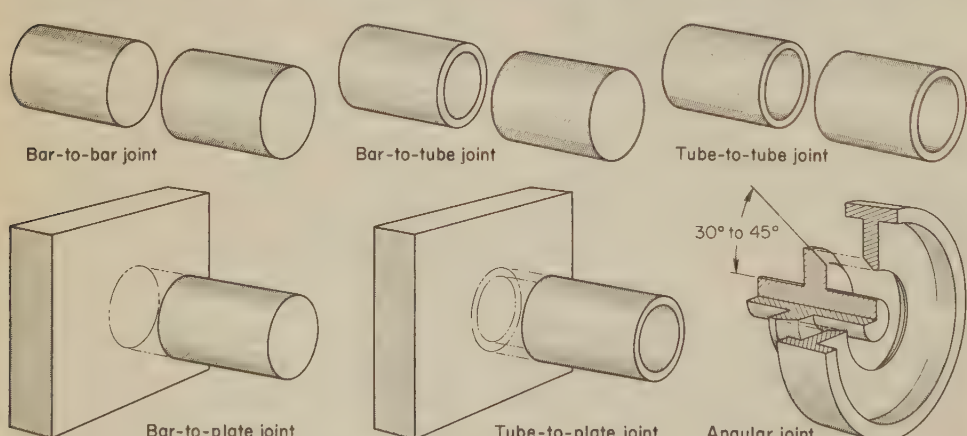


Fig. 13. Types of joints commonly made by friction welding. Bars and tubes, and joint surfaces of angular joints, must be concentric with the axis of rotation; bar, tube and plate surfaces to be welded must be perpendicular to the axis of rotation.

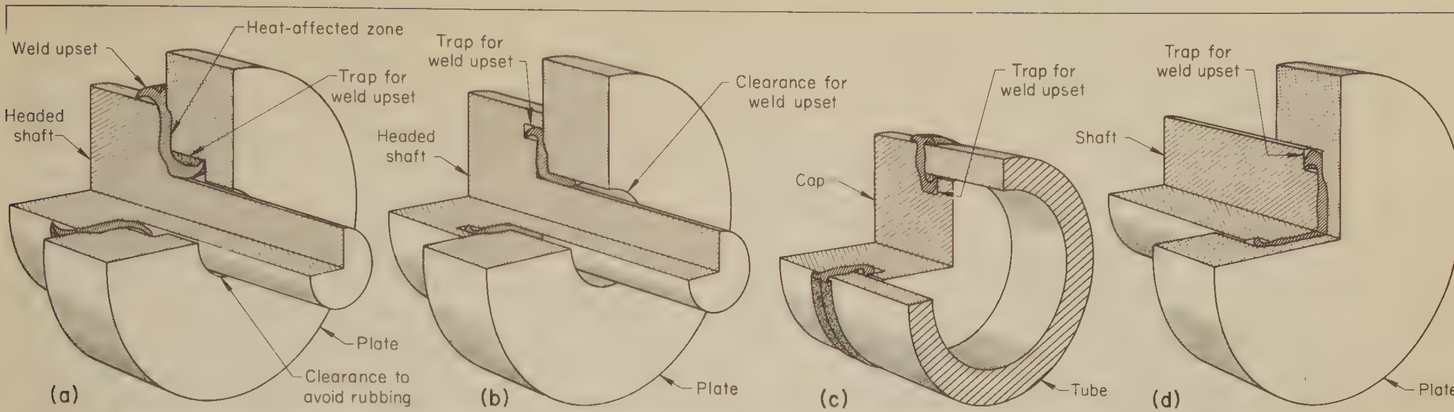


Fig. 14. Recesses used as traps for weld upset in friction welded joints. (See discussion in text, under "Design for Flow of Weld Upset".)

ward the periphery. When weld upset cannot be permitted to remain in the bore and cannot be reached for removal after welding, a trap must be incorporated into the joint design. (See the subsection on Design for Flow of Weld Upset, this page.)

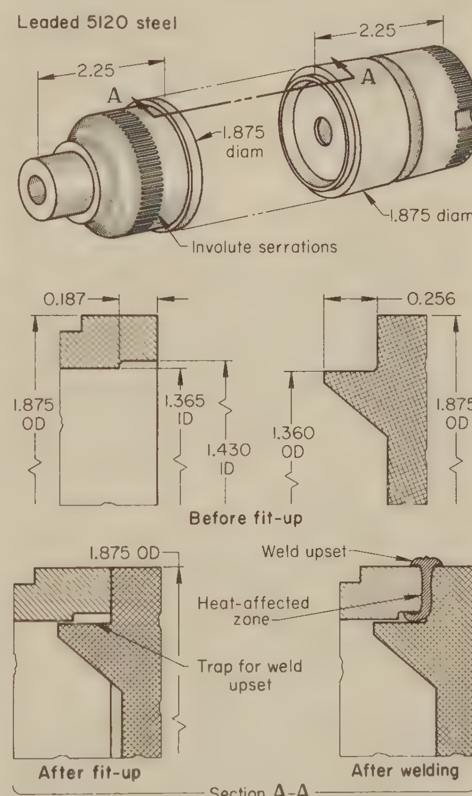
Angular joints (see Fig. 13) are used in welding the inside diameter of one component to the outside diameter of another — for instance, welding the rim of a jet-engine fan to the flange of the hub section or welding a flange to a shaft at some position between the two ends.

The joint can be made where a chamfered shoulder can be mated with an equally chamfered bore in the flange. The interfaces of angular joints must have equal included angles, and the tapered bore in the outer component must have sufficient strength to withstand the axial pressure required to make the weld.

Angular joints are usually designed with faces 30° to 45° from the centerline (an included angle of 60° to 90°) to prevent one part from being pushed through the hole in the other part. Some nickel-base alloys have been welded using smaller angles.

Design for Heat Balance. When similar metals, or dissimilar metals having about the same forging temperature and thermal conductivity, are friction welded, there are no restrictions on the relationship of the cross-sectional area of a bar or tube to the size of plate to which it is welded. Heating rates as high as 100,000 F per second make the weld cycle very short and keep heat losses to the cold metal in the plate adjacent to the weld very low. Thus, bar-to-plate and tube-to-plate welds are feasible for joining similar and some dissimilar metal combinations.

In welding dissimilar metals with widely different forging temperatures and thermal conductivities, adjustment of size or area adjacent to the weld interface may be necessary in one of the workpieces. Area differentials must be determined experimentally because each metal reacts differently. For instance, in welding a nickel-base alloy shaft 1 in. in diameter to an alloy steel shaft, the alloy steel shaft should be $\frac{1}{16}$ to $\frac{1}{8}$ in. in diameter larger than the nickel-base alloy. If the components are tubes, the inside diameter of the alloy steel tube should be $\frac{1}{16}$ to $\frac{1}{8}$ in. less than that of the nickel alloy tube. Thus the alloy steel tube would have a smaller inside diameter and a greater wall thickness and outside diameter than the nickel alloy tube. In making a cutting-tool blank, a tool steel shank can be readily welded to a tool steel body using a bar-to-plate joint, but if the shank is changed to alloy steel, the tool steel body must be modified to produce a bar-to-bar joint.



Conditions for Inertia Welding

Flywheel moment of inertia	10.75 lb-ft²
Spindle speed	2800 rpm
Weld energy(a)	14,300 ft-lb
Axial force	17,000 lb
Heat-and-weld time	0.7 sec
Machine cycle time	4 sec
Weld area	1.36 sq in.
Metal lost(b)	0.020 ± 0.003 in.
Production rate	280 parts per hour

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Joint was designed with a trap that prevented the formation of weld upset on the internal surface of the chamber.

Fig. 15. Components of a diesel-engine precombustion chamber that were joined by inertia welding (Example 459)

When a tube is welded to a thin plate with a hole of the same diameter as the inside of the tube, the hole in the plate frequently is made smaller than the ID of the tube to avoid excessive heating of the plate around the hole. This difficulty does not occur with thick plates because the metal around the hole is not heated through.

Design for Flow of Weld Upset. In applications where the presence of weld upset on one or more work-metal surfaces is undesirable, and where the upset cannot be removed after welding, traps can be incorporated into the joint design, to provide clearance for the flow of weld metal from the interface. When a plate is welded to a shaft extending through a hole in the plate, or a boss on one workpiece extends into a hole in the other workpiece, enough clearance must be provided to prevent rubbing of the shaft or boss against adjacent surfaces. Rubbing of adjacent surfaces parallel to the axis of rotation uses flywheel energy unpredictably and diminishes reproducibility of the weld.

Typical designs of traps for weld upset are shown in Fig. 14. An assembly of a headed shaft and a plate is shown in Fig. 14(a) and (b). In Fig. 14(a), weld upset could not be tolerated on the surface of the plate opposite the joint and could not be removed after welding. A counterbore in the hole in the plate, extending inward from the joint surface of the plate, served as a trap for weld upset, which was permitted to flow out around the head of the shaft. In Fig. 14(b), weld upset was not permitted on the joint surface of the plate, and the trap was formed in the head of the shaft. A surface on the head touched the plate as rotation ceased, and provided a seal.

An end-cap-to-tube weld is shown in Fig. 14(c). A tight internal corner joint free of weld metal was obtained by making the trap in the boss on the end cap. In Fig. 14(d), the step on the joint end of the shaft provided the trap for weld upset, leaving the outside corner formed by the intersection of the plate and the shaft free from upset metal.

Parts that require difficult-to-machine internal recesses or chambers can be made by joining two specially designed and machined parts. Removal of weld upset from the inside surfaces of such parts is difficult; therefore, the joint must be designed with a trap so that weld upset cannot form on the

internal surface. A trap was used effectively in the example that follows.

Example 459. Inertia Welding of a Precombustion Chamber Using a Joint Designed To Prevent Weld Upset From Forming on an Internal Surface (Fig. 15)

Precombustion chambers for diesel engines (see Fig. 15) originally were made by furnace brazing two sections together. The brazed joint was subjected to precombustion temperatures as well as a combustion pressure of about 1700 psi. Precise machining of the joint surfaces and careful inspection of the parts were needed.

When furnace brazing was replaced by inertia welding, close joint tolerances and meticulous inspection procedures were no longer needed, and product quality was improved. The mating surfaces were designed to contain the internal weld upset so that it could not flow into the chamber.

The two components were made of leaded 5120 steel in a multiple-spindle bar machine. The outside diameter of the chamber at the weld interface was 1.875 in., and the width of the weld interface was about 0.22 in. A small enclosed internal cavity, shown in Fig. 15 (section A-A, after fit-up), contained the internal weld upset and prevented it from flowing into the chamber. Involute serrations were rolled onto each part during the machining operation to aid the hydraulically operated welding-machine collet chucks in gripping the workpieces, and mating serrations were machined in the collet pads of the chucks. Dependable holding techniques were needed to prevent undesirable malfunctions, to reduce wear on the gripping surface of the chuck, and to minimize upkeep cost.

In operation, the two sections were clamped in their respective collet chucks, and the tailstock was moved forward until the surfaces to be welded were 0.045 in. apart. The inertia flywheel and spindle were accelerated to 2800 rpm (in about 1.2 sec), the energy source was disconnected from the spindle and, immediately, the two sections were brought into contact under a force of 17,000 lb, which remained constant until rotation stopped. Heat-and-weld time was 0.7 sec. Strength of the welded joint was equal to that of the base metal.

The spindle chuck unclamped automatically and the tailstock retracted to the starting position. Then the tailstock chuck unclamped automatically and the workpiece was removed manually and was placed in an automatic lathe where the weld upset was machined off while the next piece was being welded.

Machine cycle time, exclusive of handling time, was 4 sec. Metal lost was 0.020 ± 0.003 in. Total cost of operation, including overhead, was $0.035 per weld.

Additional welding conditions are given in the table with Fig. 15.

Design for Machine Size. The amount of energy needed for friction welding depends partly on the distance metal must be extruded from the innermost point of the interface of the workpieces. Thus, more weld energy is required, per square inch of weld area, for joining two 1-in.-diam bars than for joining a 1-in.-diam bar to a 1-in.-diam tube. The joints are of nearly equal strength, because the metal at the center of the bar is near the neutral axis and contributes very little to torsional or bending strength.

Some joints can be designed with a center relief in one or both workpieces to eliminate the nonworking but hard-to-weld metal at the center. This also may permit the part to be welded on a smaller-capacity machine, or the length of the welding cycle to be reduced. The size of the center relief must be large enough so that compres-

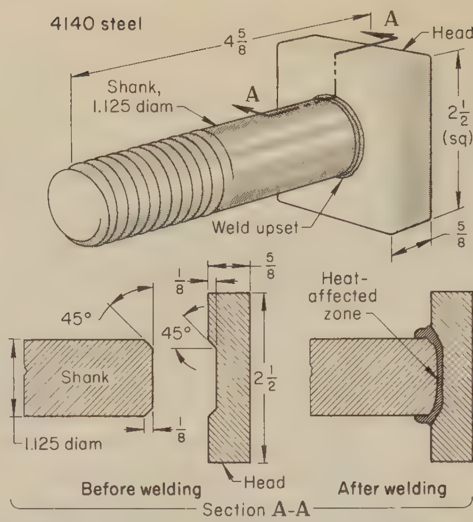
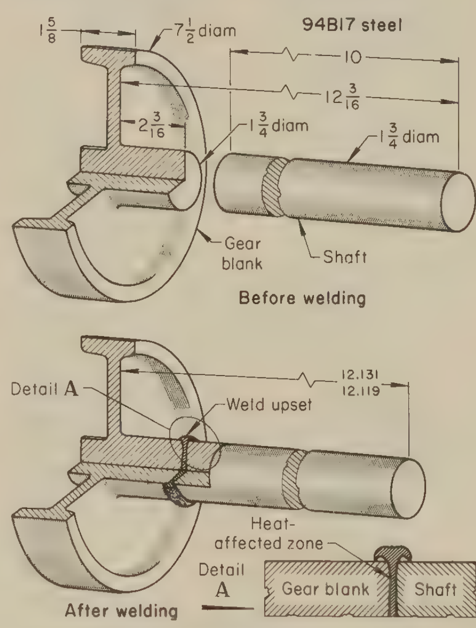


Fig. 16. Square-head bolt that was made by inertia welding to reduce costs from original method of machining from solid bar stock (Example 460)

sion of the entrapped air will not cause a weld defect, and to provide adequate space for the weld upset.

Similarly, a bar-to-plate joint can be redesigned as a tube-to-plate or a bar-to-bar joint if desirable to bring it within the capacity of a particular machine. A bar-to-bar joint requires less energy than a bar-to-plate joint.



Conditions for Inertia Welding

Machine capacity:	
Part diameter	0.875 to 2.5 in.
Spindle speed	4800 rpm max
Axial force	160,000 lb max
Flywheel moment of inertia	170 lb-ft²
Spindle speed	2500 rpm
Weld energy(a)	180,900 ft-lb
Axial force	45,000 lb
Floor-to-floor time	2 min (approx)
Weld area	2.4 sq in.
Metal lost(b)	0.062 ± 0.006 in.

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Fig. 17. Gear-blank-and-shaft assembly that was joined by inertia welding. Floor-to-floor time was reduced by 90% compared with original method of pressure gas welding. (Example 461)

Control of Weld Quality

Inspection of friction welds usually consists of visual examination of the weld upset and measurement of the over-all length of the assembly to determine the variation in axial shortening of the members during welding.

Variation in axial shortening, or metal lost, is a good indication of weld quality. Because rotational speed and heating and welding pressures are readily controlled within close limits, the amount of metal lost usually is within ±5% of the nominal value. Therefore, when the lengths of the workpieces are held to close tolerances, the expected variation in the over-all length of the welded assembly can be calculated using the tolerances of the workpieces and weld upset. The nominal amount of metal lost can be determined while making tests to establish welding conditions.

Tension, bend, impact or fatigue tests frequently are used to check weld quality. Sectioning for microscopic examination and for hardness tests is also performed on test samples or on randomly selected production parts.

Proof testing by bending just enough to cause slight yielding in the weld zone has been used for testing friction welded pump shafts. Defective welds are discovered but no harm is done to satisfactory welds. Magnetic-particle inspection can be done on steel parts after the weld upset has been removed.

Friction Welding vs Other Processes

Friction welding can replace or supplement other manufacturing processes to reduce machining and material costs, to permit the use of work metals that meet the application requirements, and to provide reliable joints.

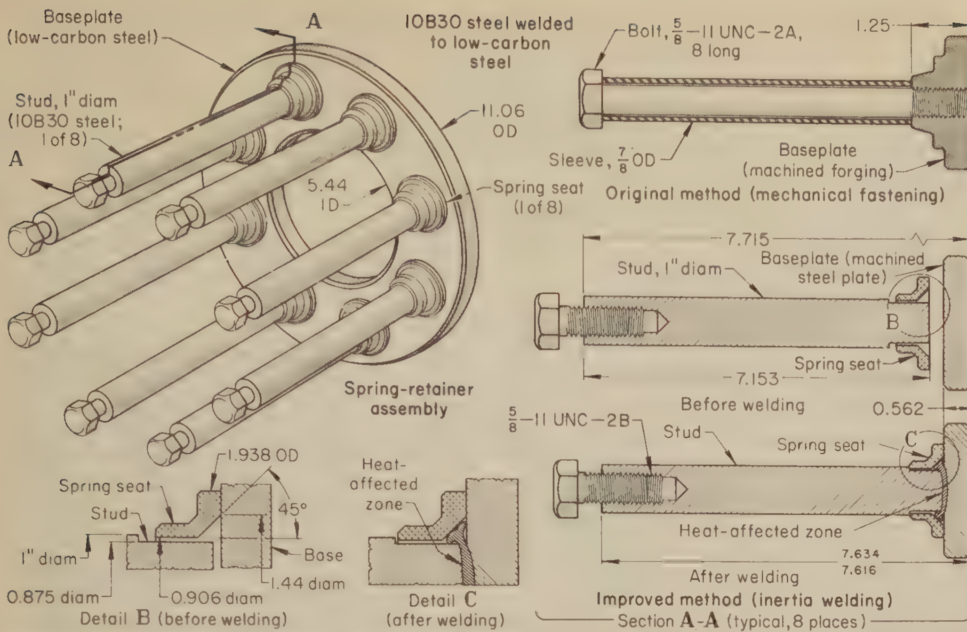
In Example 451, machining and material costs were reduced by friction welding stub shafts to a rotor body instead of machining from solid bar stock. The quality of friction welded parts can be equal to that of parts machined complete from bar stock, as illustrated by the following example.

Example 460. Change From Machining to Inertia Welding That Reduced the Cost of Making Square-Head Bolts (Fig. 16)

The square-head bolt shown in Fig. 16 originally was machined from 2½-in.-sq 4140 steel bar and heat treated to the required mechanical properties. Cost of each bolt was $6.03.

When machining from solid bar stock was replaced by inertia welding a shank to a bolt head, there were no changes in the over-all quality, serviceability and appearance of the bolt, and cost was reduced to $2.707, for a saving of $3.323 per bolt. The welded bolts, when tested in accordance with SAE standard J429, met the requirements for Grade 7 threaded fasteners. Annual production was 1000 bolts.

In the improved method, the two workpieces were made of 4140 steel in an automatic bar machine. The head was faced, recessed and cut off from a 2½-in.-sq bar. The shank was turned, chamfered, threaded and cut to length from a 1¼-in.-diam bar. The mating surfaces of the shank and head had matching contours, as shown in Fig. 16, to assist in alignment. After inertia welding, the bolt was normal-



Conditions for Inertia Welding

Flywheel moment of inertia	8.5 lb-ft²	Heat-and-weld time	1.5 sec per weld
Spindle speed	3900 rpm	Weld area	0.60 sq in.
Weld energy(a)	22,000 ft-lb	Metal lost(b)	0.090 ± 0.009 in.
Axial force	11,000 lb	Production rate	15 parts per hour

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Fig. 18. Spring-retainer assembly made by inertia welding eight studs to a baseplate at lower cost than by tapping a forged plate and inserting bolts (Example 462)

ized, the weld upset was trimmed to a ⅛-in.-radius fillet, and then the bolt was quenched and tempered. About 1⁄16 in. of metal was lost during upsetting.

Sectioning and macroetching the weld zone showed a sound weld. Microscopic examination after heat treatment disclosed an area of transition of finer grain size between the base metal and weld area.

In the example that follows, production time was reduced 90% and rejection rate was reduced slightly when pressure gas welding was replaced by inertia welding for joining a forged gear blank to a shaft.

Example 461. Change From Pressure Gas Welding to Inertia Welding That Reduced Production Time by 90% (Fig. 17)

The 94B17 steel gear-blank-and-shaft assembly shown in Fig. 17 originally was joined by pressure gas welding. The two parts were machined flat at the interface without use of a cutting fluid, and then were chucked in a modified lathe equipped with a hydraulically actuated tailstock and an adjustable oxyacetylene ring burner on the bed. The parts were brought together, heated to slightly below the melting range and held under pressure until the weld was completed. Weld quality was good, and rejection rate was approximately 0.5%. However, 20 min was required for loading, heating, welding and unloading each part.

To increase the production rate, the joining method was changed to inertia welding. No changes in part design or joint preparation were required.

The gear blank was placed in a chuck that was attached to the spindle, and the shaft was chucked in the nonrotating tailstock. The spindle was accelerated to 2500 rpm, the drive mechanism was disengaged, and the workpieces were brought together with an axial force of 45,000 lb. The weld was completed when the flywheel energy was exhausted and the flywheel came to rest.

Although some latitude existed in the selection of machine settings, excellent results were obtained by using the conditions given in the table with Fig. 17. A relatively high axial force was needed to obtain the desired weld upset because of the strength of the 94B17 steel at elevated temperature. Total axial shortening of the workpieces (metal lost) was 0.062 ± 0.006 in.

The change from pressure gas welding to inertia welding reduced floor-to-floor time per assembly to approximately 2 min, and reduced the rejection rate to 0.2%. Weld quality was checked by ultrasonic and magnetic-particle inspection after removal of the weld upset.

Redesign of the workpieces in the following example allowed inertia welding to replace forging and machining. An assembly of equivalent quality was produced at lower cost.

Example 462. Redesign of a Spring-Retainer Assembly for Production by Inertia Welding To Reduce Costs (Fig. 18)

A spring-retainer assembly (see Fig. 18) for a heavy-duty tractor steering clutch originally was made from a forged, machined and tapped baseplate into which hexagon-head bolts were inserted. Spring seats were coined in the base plate prior to machining. The height to which the bolts extended above the baseplate was maintained by a sleeve made of ⅞-in.-OD tubing. When the product design was changed so that studs could be inertia welded to a steel plate, the cost of each assembly was reduced by $0.71.

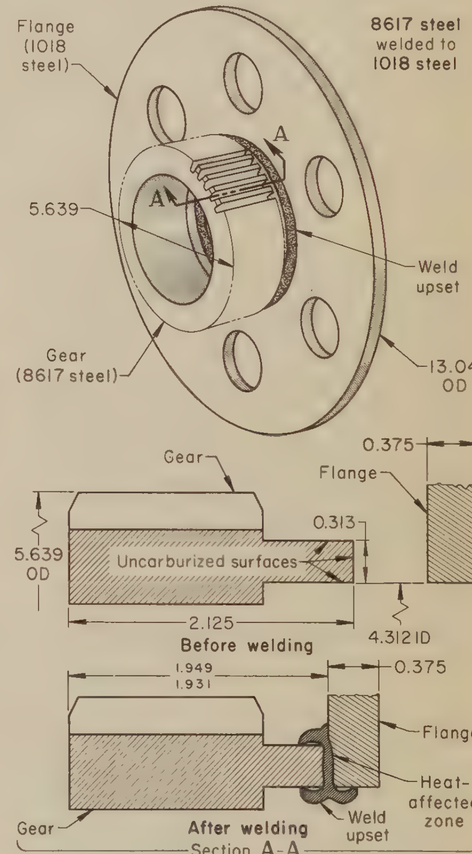
In the improved method, the baseplate was gas-cut from a ⅞-in.-thick low-carbon steel plate. The inside and outside diameters were turned to the dimensions shown in Fig. 18, and were then ground flat to a thickness of 0.562 in. The spring seats were made in an automatic bar machine from 1 15⁄16-in.-diam 1213 steel bar stock. The studs were machined from 1-in.-diam 10B30 cold finished steel that had been heat treated to a hardness of Rockwell C 23 to 30. One end of the stud was tapped with a ⅝–11 UNC–2B thread, and the other end was machined to 0.875 in. in diameter, which produced a weld area of 0.60 sq in. The parts were degreased before being inertia welded.

The baseplate was located by its inside diameter in an indexing fixture that was manually indexed 45° between successive welds. A manually loaded, hydraulically actuated collet chuck was mounted on the spindle for gripping the 1-in.-diam studs.

In operation, the baseplate was secured in the indexing fixture, a stud was clamped in the collet chuck, and a spring seat was placed over the 0.875-in.-diam end of the stud. Rotation of the spindle did not begin until the tailstock had advanced to a position that prevented the spring seat from falling off the end of the stud. The weld upset was not removed, because it was covered by the spring seat. Heat-and-weld time was 1.5 sec per weld, and production rate was 15 assemblies per hour. Additional welding conditions are given with Fig. 18.

Weld quality was checked by visually inspecting the weld upset, and the distance from the bottom of the baseplate to the top of the studs was measured for compliance with a specification of 7.625 ± 0.009 in.

In the example that follows, the method of making a flanged transmission gear was changed from forging to



Conditions for Inertia Welding

Flywheel moment of inertia	668 lb-ft²
Spindle speed	1450 rpm
Weld energy(a)	239,000 ft-lb
Axial force	105,000 lb
Heat-and-weld time	2 sec
Weld area	4.55 sq in.
Metal lost(b)	0.185 ± 0.009 in.
Production rate	63 parts per hour

(a) Calculated from flywheel size (moment of inertia) and spindle speed. (b) Total axial shortening of the workpieces during welding.

Fig. 19. Flanged transmission gear that was made by inertia welding instead of by forging, to reduce costs and avoid distortion of the flange during heat treatment (Example 463)

inertia welding to allow selective hardening of the gear section and so avoid flange distortion. The inertia weldment weighed and cost less than the forging.

Example 463. Change From Forging to Inertia Welding To Avoid Workpiece Distortion (Fig. 19)

A flanged transmission gear originally was machined from a one-piece 8617 steel forging. Hardening of the gear section was required, and distortion of the large-diameter flange necessitated press-die quenching. Although not required functionally, a 0.64-in.-thick by about 1-in.-wide rim was needed to minimize distortion of the 0.335-in.-thick flange during heat treatment. To locate the forging during die quenching, annular surfaces were machined on the flange opposite the gear and on the rim to an axial dimension of 0.100 ± 0.001 in. Because of the cost of alloy steel forgings and the problems from distortion during heat treatment, the gear was redesigned for inertia welding, as shown in Fig. 19.

The flange section was gas-cut from scale-free 1018 steel plate 0.375 in. thick, machined to a 13.04-in. OD and a 4.312-in. ID, and degreased. The gear section was hobbed from 8617 steel tubing and carburized. Before hardening, the carburized case was machined off at the end and sides of the joint area, so that the weld would be made on the low-carbon 8617 core, not on the carburized surface. The area of the weld surface was about 4.55 sq in. The gear section was hardened before welding, and thus heat treatment of the entire part and the resulting distortion of the flange were avoided.

The flange section was held in a nonrotating fixture mounted to the tailstock of the inertia welding machine and the gear was held in a rotating fixture mounted on the spindle. Locating and driving were done on the pitch diameter of the gear. The machine was loaded and unloaded manually. After the gear was welded to the flange, the weld upset was machined from the inside and outside surfaces, and spline teeth were hobbed around the periphery of the flange.

Welding conditions (see table with Fig. 19) and machine performance were checked for each production lot. The weld upset on each part was visually inspected, and random measurements were made to determine whether the length of the gear conformed to the specified 1.940 ± 0.009 in.

Inertia welding and machining produced a part with quality equivalent to that of the machined forging, but at a cost reduction of $4.25 per piece.

Cost of Inertia Welding vs Other Methods of Fabrication

The cost advantages of inertia welding in comparison with other methods of fabrication are shown in the following projections of costs for the production of three different parts.

Drill-to-Shank Welding. Costs for flash welding and inertia welding of 4140 steel shanks to M10 high speed tool steel drill bodies, indicating the savings provided by inertia welding, are given in Table 3.

Table 3. Cost Comparison for Joining M10 High Speed Tool Steel Drill Bodies to 4140 Steel Drill Shanks by Flash Welding and by Inertia Welding

Item	Drill A: Flash welding	Drill A: Inertia welding	Drill B: Flash welding	Drill B: Inertia welding	Drill C: Flash welding	Drill C: Inertia welding
Drill Dimensions, In.						
Diameter	0.547		0.832		1.062	
Over-all length	8.25		9.75		11.00	
Body length	4.25		5.75		6.25	
Welding Conditions						
Metal lost (total), in.	0.400	0.120	0.510	0.175	0.620	0.200
Metal lost (high speed tool steel), in.	0.240	0.030	0.305	0.045	0.370	0.060
Production rate, welds per hour	165	225	138	190	84	160
Scrap rate, %	5	0.5	5	0.5	5	0.5
Costs per 100 Pieces(a)						
Body stock	$38.88	$37.06	$121.10	$115.90	$216.08	$205.96
Shank stock	4.58	4.49	10.93	10.74	21.48	21.00
Welding labor	9.34	6.65	10.72	7.90	17.69	9.38
Cutoff labor	5.00	5.00	6.00	6.00	7.00	7.00
Scrap loss	2.89	0.26	7.44	0.70	13.11	1.21
Total cost	$60.69	$53.46	$156.19	$141.24	$275.36	$244.55
Savings	...	$7.23	...	$14.95	...	$30.81

(a) Values used in calculations: M10 high speed tool steel, $1.30 per pound; 4140 steel, $0.17 per pound; labor plus burden, $12 per hour; labor efficiency, 80%.

Assuming the quantity of 0.547-in.-diam drills (drill A, Table 3) to be about three times that of drills B and C, the average saving per drill would be $0.136 — which, at 300,000 drills per year, would give annual gross savings of $40,800. The inertia welding machine and semiautomatic tooling would cost about $60,000.

Shaft-and-Pinion: One-Piece Forging vs Weldment. Table 4 compares costs for two sizes of each of two designs of pinion-and-shaft one-piece upset forgings made of 8630 steel and equivalent parts made by inertia welding an 8630 steel pancake or upset forging to a 1035 steel tube or shaft. The two designs, identified as designs A and B, are illustrated in Table 4 as the weldments after cutting of gear teeth.

The cost savings shown for the inertia welded pinion-and-shaft assemblies accrue from the use of less expensive forgings, the lower cost of 1035 steel than of 8630 steel for the shafts, and elimination of a drilling operation for the hollow shaft on design A. The inertia welding machine and tooling would cost about $100,000.

Cluster Gear. Following preliminary machining, a heavy gear-and-pinion cluster, upset forged in one piece from 8822 carburizing steel, presented problems in quench hardening after carburizing to provide a case hardness of Rockwell C 60 and a core hardness of Rockwell C 35. A rather severe quench was needed to develop the required core hardness in the heavier pinion section of the forging, and this resulted in excessive distortion and occasional cracking at the intersection of the web and gear. Although increasing the web thickness might have solved the problem, it would have increased the as-forged weight of the one-piece cluster from 130 lb to 152 lb.

To solve the problem and reduce manufacturing costs, investigation was made (*a*) on a change to an inertia welded assembly of a forged gear blank and a forged pinion blank, and (*b*) on the selection of a carburizing steel with slightly higher hardenability for the heavier pinion forging.

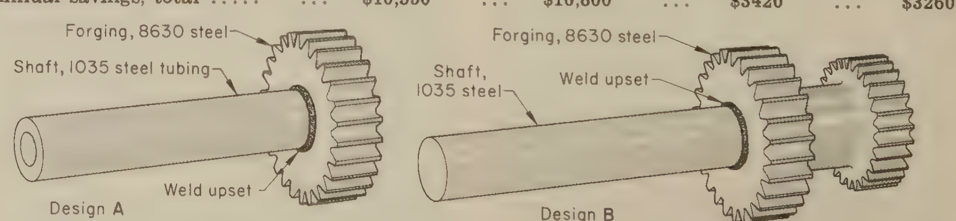
The cost of the inertia welding machine, equipped for manual loading and with semiautomatic tooling, was about $225,000. With a machine cycle time of 4 min, production rate was projected at 13.8 assemblies per hour.

Following is a comparison of costs for the two methods of fabrication:

Cost factor	Cost
Original forging, 130 lb at $0.25 per pound	$32.50
Improved forging, 122 lb at $0.23 per pound	28.06
Material saving per piece	$ 4.44
Inertia welding labor and burden, 0.075 hr at $11 per hour	0.82
Cost saving per piece	$ 3.62
Cost saving per hour (13.8 assemblies per hour × $3.62)	$50.00

Table 4. Costs for Making Two Sizes of Two Designs of Pinions as One-Piece Upset Forgings and as Inertia Weldments of Pancake or Upset Forgings and Shafts (Illustrated Below)

Cost factor	Pinion design A, 7 in. long; 7500/yr: Upset forging	Inertia welding	Pinion design A, 5½ in. long; 10,000/yr: Upset forging	Inertia welding	Pinion design B, 11 in. long; 6000/yr: Upset forging	Inertia welding	Pinion design B, 15 in. long; 2000/yr: Upset forging	Inertia welding
Weight of forging, lb	14.5	12.0	5.6	3.6	11.3	6.9	29.1	19.3
Comparison of Costs(a)								
Cost of forging	$3.19	$2.28	$1.22	$0.68	$2.49	$1.52	$6.40	$4.25
Cost of drilling shaft	0.92	...	0.92	...	...	...	...	...
Cost of shaft stock	...	0.36	...	0.29	...	0.31	...	0.43
Welding labor cost	...	0.09	...	0.09	...	0.09	...	0.09
Total cost per piece	$4.11	$2.73	$2.14	$1.06	$2.49	$1.92	$6.40	$4.77
Savings per piece	...	$1.38	...	$1.08	...	$0.57	...	$1.63
Annual savings, total	...	$10,350	...	$10,800	...	$3420	...	$3260



(a) Based on unit costs as follows: upset forgings, $0.22 per pound; pancake forgings, $0.19 per pound; bar stock, $0.07 per pound; 1.5-in.-diam tubing, $0.86 per foot; and labor and burden, $11 per hour.

ELECTRON BEAM WELDING

*By the ASM Committee on Electron Beam Welding**

CONTENTS

IN ELECTRON BEAM WELDING, the joint to be welded is heated by bombarding it with a dense stream of high-velocity electrons. The kinetic energy of the electrons is changed into heat on impact with the work.

The electron beam is produced in a high-vacuum environment by an electron gun, usually consisting of a tungsten or tantalum cathode, a grid or forming electrode, and an anode. Electrons are emitted from the cathode, which is heated to about 4600 F or higher. The electrons are gathered, accelerated to a high velocity and shaped into a beam by electrical fields between the cathode, grid and anode. The beam is collimated and focused by passing through the field of an electromagnetic focusing coil, or "magnetic lens". Electron beams can be deflected from their normal path by magnetic deflection coils, usually located below the focusing coil.

The gun, which is sometimes isolated from the welding chamber by a valved aperture, is held at a high vacuum (10^{-4} to 10^{-5} torr, or less) to protect its components, especially the cathode, from oxidation and from short-circuiting through vapors evolved in welding. The vacuum environment also reduces electron scattering by air molecules, thus conserving effective beam energy. Electron guns are rated at about 30 to 175 kv, and for a beam current of about 50 to 1000 ma.

Beams typically are focused to about 0.010 to 0.030 in. in diameter and have a power density of about 10^6 watts per square inch, which is sufficient to vaporize any metal. In the welding process, the beam first creates a hole in the work. As the electron beam advances along the joint, a weld is formed by a combination of three effects that occur at the same time: (*a*) metal on the leading side of the hole vaporizes, and the vaporized metal then condenses to form molten metal on the trailing side of the hole; (*b*) the molten metal on the leading side of the hole flows to the trailing side of the hole; and (*c*) the molten metal thus formed continuously fills the hole and solidifies as the electron beam advances.

Applicability

Electron beam welding is used to weld almost any metal that can be arc welded; weld quality in most metals is equal or superior to that of the best gas tungsten-arc welds. The major advantages of vacuum electron beam welding include:

1. Ability to make welds that are deeper, narrower and less tapered than arc welds, with a total heat input much lower than that in arc welding
2. Superior control over penetration and other weld dimensions and properties
3. A high-purity environment for welding (evacuated work chamber), resulting in freedom from impurities such as oxides and nitrides
4. Higher welding speed
5. High production when a number of parts can be loaded in a chamber, or when the chamber is small enough to permit rapid pumpdown.

These characteristics make possible: minimizing distortion and shrinkage in welding; welding of hardened or work-strengthened metals and frequently without significant deteriora-

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Some of the examples presented in this article were contributed by members of other Metals Handbook welding committees.

tion in mechanical properties at the joint; welding of parts that already have been finished to final assembly dimensions; welding in close proximity to heat-sensitive components or attachments; readily making hermetic-seal closure welds on evacuated enclosures; welding of refractory and reactive metals; and welding of combinations of dissimilar metals not usually joinable by arc welding. By projecting the beam several inches to several feet, welds often can be made in otherwise inaccessible locations.

Disadvantages of vacuum electron beam welding include:

1 High cost of equipment. Production-size welding units vary considerably in cost, depending on the accessories included, but a general-purpose unit may cost more than $150,000 (1971 prices).
2 High cost of precision joint preparation and precision tooling, usually higher than for arc welding processes. Because of the relatively small size of the electron beam, joint gaps must be kept to a minimum.
3 Limitations of the vacuum chamber. Work size is limited by the chamber dimensions, and production rate and unit welding cost are adversely affected by the need to pump down the work chamber for each load.

Nonvacuum electron beam welding is not subject to the limitations of the vacuum chamber, can be done at high welding speed, and may permit savings in comparison to arc welding on mass-produced parts of suitable shape. It offers the first two advantages listed on page 519 to a lesser degree than does vacuum electron beam welding, and it completely lacks the third advantage over arc welding.

Penetration is usually less than ½ in., and workpiece shape must permit a working distance of ¾ in. or less.

Process Control

The basic variables for controlling vacuum electron beam welding are:

1 Accelerating voltage
2 Beam current
3 Welding (travel) speed
4 Focusing current
5 Distance from gun to work.

Beam spot size (at the work) is determined by the characteristics of the electron gun, the focusing current (which controls the focal length of the beam), distance from gun to work, accelerating voltage, and beam current.

Increasing the accelerating voltage or beam current increases depth of penetration; the product of these two variables (called beam power) determines the amount of metal melted. Increasing welding (travel) speed without changing another process variable reduces depth of penetration almost proportionately and reduces weld width somewhat. Changing any of the other four basic control variables so as to increase beam spot size reduces depth of penetration and increases weld width, if welding speed is not changed.

Beam deflection can be used to change the impact angle of the beam or to produce controlled patterns of beam oscillation for the effect of greater beam spot size or other special effects, and the beam can be pulsed to reduce effective beam power (page 548).

In nonvacuum electron beam welding, ordinarily all of the five basic control variables except beam current are preset, and control is based on beam current. Beam current may be set at a fixed value for the application and merely turned on and off in relation to workpiece travel, or it may be programed to vary in a predetermined pattern. Beam deflection cannot be used; beam oscillation is seldom used.

Operations

The tooling and welding procedures for each application are developed in preliminary experimental work. Details of the welding sequence may vary somewhat, depending on differences in equipment and on the application requirements. One typical sequence for welding in high vacuum is:

1 Assemble and prepare work and fixtures for welding. This includes cleaning, and may include demagnetizing, preheating and tack welding.
2 Load fixtured work on worktable or workholding mechanism in welding chamber.
3 Start chamber pumpdown.
4 Make preliminary alignment of joint with defocused beam, after pumpdown.
5 After chamber pressure has been reduced to 10^{-4} torr, focus on tungsten target block and set beam parameters.
6 Make final alignment of joint to the beam position.
7 Start welding. Welding is usually performed automatically, but can be performed manually.
8 Terminate the welding cycle.
9 When the work has cooled sufficiently, admit air to the chamber and remove fixtured work.

Step 5 above applies primarily to setting up for a repetitive operation.

For nonvacuum welding, the electron gun and beam transfer column are maintained at established pressure levels. Work-handling and welding operations in this method are ordinarily mechanized for high-speed production, and work and fixturing are prepared before a production run is begun or are done as part of a production-line operation. Beam parameters, alignment of joint with beam position, and transfer and movement of work for welding are set before a production run. Alignment of the joint with beam position is only slightly less critical than for vacuum electron beam welding, because beam spot size and weld width are only slightly larger for nonvacuum welding.

Mechanical Preparation of Joint. A joint for electron beam welding ordinarily has closely fitted, abutting, square groove faces, and filler metal is not ordinarily used. As a general rule, the faces of the joint are machined to a surface roughness of about 120 micro-in. or less.

Surface finish on the weld groove faces may not be critical, depending on part and joint design and the requirements for weld properties. In studies on butt welding of 2-in.-thick aluminum alloy 2219 and Ti-6Al-4V in which the groove faces had surface roughness values of 63, 125, 250, 500 and 1000 micro-in., surface finish had no effect on weld quality, as determined by visual examination and x-ray radiography; all welds were sound. Edge surface finish is much less critical on broad welds than on narrow welds.

Edge roughness is not critical on lap joints in thin metal as long as burrs do not separate the surfaces.

Fit-up. A butt joint is not open, as in arc welding, but has closely fitted, straight surfaces to enable the characteristically narrow electron beam to fuse base metal on both sides of the joint in making a weld. The members of a joint to be melt-through welded also are closely fitted. Fit-up tolerance depends on work-metal thickness and joint design, but is usually 0.005 in. or less. Joint gap is usually smaller for thin work metal and unbacked joints; it may be 0.001 or 0.002 in. max. Interference fits are sometimes used where shrinkage can cause cracking, as in circular joints on hardenable metals.

Joint gap of about 0.002 or 0.003 in. max is commonly used for making narrow welds.

In making deep welds, poor fit-up or excessive joint gap can cause excessive shrinkage, underfill, undercut, voids, cold shuts and missed joints. In most metals, joint gap should not exceed 0.010 in. for narrow welds deeper than about ½ in., although sound welds have been obtained using joint gaps of 0.030 in. by increasing weld width to 0.275 in.

Cleaning. Workpiece surfaces must be meticulously clean for electron beam welding. Inadequate surface cleanness not only causes weld defects, as it does in arc welding, but also increases pumpdown time and can degrade the oil used in the pumps.

Any of the common chemical and mechanical cleaning methods may be used (see cleaning sections in the articles on arc welding processes in this volume). A combination of two or more methods is often used. If workpieces are cleaned in chlorine-containing compounds these compounds should be removed by another cleaning method before welding.

Final cleaning should be done within a few minutes before welding. After final cleaning, the joint faces should not be touched by hands or tools.

Fixturing methods for vacuum electron beam welding are generally like those for gas tungsten-arc welding of precision parts without the use of filler metal, except that the clamping force needed is usually lower, and all materials and moving members must be suitable for use in a high vacuum.

Because total heat input to the weld is much less than for arc welding and because the heat is highly localized, there is less need for heavy fixturing, massive heat sinks, or water cooling. C-clamps suffice for many parts. In some applications, clamping can be supplemented or replaced by small tack welds or by a shallow weld pass (sealing pass) over the joint, with the penetration weld made later at full power. Both basic and specialized fixturing are available.

General-purpose welding positioners and related mechanisms are satisfactory for nonvacuum electron beam welding. Locating and aligning mechanisms are simpler than for welding in a vacuum, because of their accessibility and because beam widths for nonvacuum welding do not necessitate such high accuracy in tracking the joint. Maintenance of work-handling equip-

ment for nonvacuum electron beam welding is greatly simplified by its out-of-chamber location.

Demagnetization. Workpieces and fixtures made of magnetic materials should be demagnetized before welding. Residual magnetism may result from magnetic-particle testing, magnetic chucks, or electrochemical machining. Even a small amount of residual magnetism can cause beam deflection.

Workpieces are usually demagnetized by placing them in a 60-cycle inductive field and slowly removing them. The equipment used in magnetic-particle testing can be used (see Example 484).

Before welding, workpieces should be checked with a gauss meter. Acceptable gauss-meter readings vary from ½ gauss for very narrow, critical welds to as much as 10 gauss for relatively wide welds.

Pumpdown time for the vacuum chamber depends mainly on chamber size, types of pumps used, and vacuum required. Vacuum controls on electron beam welding equipment generally provide a choice of either an automatic or a manual mode of pumpdown. In the manual mode, the operation of the vacuum system is controlled by a manual selection switch on the operator's console, which, step by step, sequences all valves and instrumentation through the entire vacuum cycle. In the automatic mode, a series of relays, limit switches, and pressure sensors overrides the manual selector switch.

For high-vacuum electron beam welding, a pressure of 10^{-4} torr or less is produced by a mechanical-piston pump operating in conjunction with an oil-diffusion pump. The sizes of these pumps depend on the size of the chamber and the pumpdown time required. A 30-cu-ft chamber employing a 21,000-cu-ft-per-minute diffusion pump and a 140-cu-ft-per-minute mechanical pump could be expected to reach welding pressure in less than 3 min; a 300-cu-ft chamber employing a 42,000-cu-ft-per-minute diffusion pump and a 600-cu-ft-per-minute mechanical pump could be expected to pump down in less than 10 min.

For electron beam welding in medium vacuum, the pressure in the work chamber is 2×10^{-1} to 10^{-3} torr. The gun chamber, in which the beam is generated, collimated and focused, is held at 10^{-4} to 10^{-5} torr, as in high-vacuum welding. A small diffusion pump is needed to provide the vacuum in the gun chamber, but a diffusion pump is not needed for pumping down the welding chamber, which can be evacuated with a mechanical pump.

In some applications, however, a blower or Roots pump may be required for high-production welding of small parts in a medium vacuum. Pumpdown times in mass production often range from about 40 sec for a relatively large general-purpose working chamber (4 cu ft), down to less than 5 sec for small chambers.

Preheat and Postheat. Most commonly welded metals can be electron beam welded, even in thick sections, without preheating, because of the extremely narrow width of the heat-affected zone. Hardenable and difficult-to-weld metals may need to be

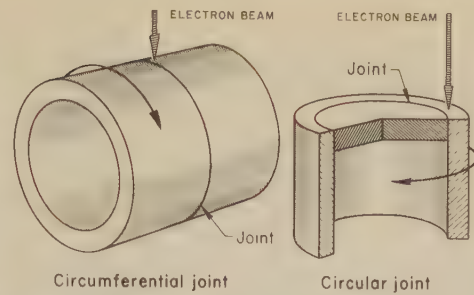


Fig. 1. Circumferential and circular joints in position for electron beam welding

preheated, especially for thick sections and where the weld is restrained.

High-strength alloy steels and tool steels thicker than about ⅜ in. ordinarily must be preheated before electron beam welding, to prevent cracking. Deep circular welds, especially partial-penetration welds, in thick sections of carbon steel containing more than about 0.35% carbon usually need preheating. On the other hand, welds subject to less restraint, such as circumferential welds on cylindrical shapes, can be made on ½-in.-thick, 0.50% carbon steel without preheating.

Preheating, when needed, is usually done before the work is placed in the work chamber. Selection of heating method depends on the size and shape of the work and the preheat temperature; a combination of methods can be used. Torch and furnace heating are widely used; induction and infrared-radiation heating are also used. On small parts or where distortion from localized heating is not a problem, and where increased cycle time can be tolerated, heating is sometimes done with a defocused electron beam; this method can also be used to supplement other methods of heating.

Furnace preheating was used in Examples 483 and 488. The electron beam was used at reduced power to preheat tantalum in Example 491.

When postheating is employed on electron beam welded parts, it is ordinarily done by conventional means after removing the work from the welding chamber.

Postheating was done in 13 of the 42 examples described in this article. Stress relieving was done in Examples 464, 484, 487, 490, 502 and 503, tempering in Examples 464, 473, and 486.

Operating Conditions. A typical vacuum welding sequence is listed in column 2 on the preceding page. Starting and stopping the weld usually requires special consideration, to avoid nonuniformity of the weld at these points and possible burn-through and loss of metal.

One technique that is used to avoid these difficulties is to start the weld at full beam power on a starting tab of the work metal that is tightly fitted against one end of the joint, and to conclude it on a runoff tab at the other end of the joint. Or, the workpieces can be made oversize to provide extra material for starting and stopping. The tabs or the extra material can be machined off after welding. Starting and runoff tabs are used mostly in low-production operations.

Another technique is to start and stop the weld on the work, bringing up the current gradually (upslope) at the beginning of the weld and reducing it gradually (downslope) at the end of the weld. Upslope and downslope at controlled rates and time intervals, as established for a specific application, can be programed into the welding procedure. The use of upslope and downslope is of special value where the weld is a closed path, as in welding circular and circumferential joints.

In many applications of closed-path welds, the weld can be started at full power, with downslope at the end providing a sufficiently gradual termination and a suitable distance of overlap. Downslope of current after overlapping the beginning of the weld on circular welds in thick sections of high-hardenability steels is critical, to avoid porosity and cracking. Other parameters may also be adjusted to avoid these defects.

Downslope alone was used in welding 15 circular and circumferential joints in examples described in this article, and both upslope and downslope were used on five circular and circumferential joints. Upslope is usually rapid; downslope is from a few degrees to a major portion of a revolution.

A "cosmetic pass" is made when needed to smooth or flatten the crown of a weld that is irregular or too high, or to correct undercut or underfill. The beam is usually defocused or reduced in power, or both, in making a cosmetic pass. Filler metal may also be added in making a cosmetic pass intended to correct undercut or underfill.

Cosmetic passes were used on vacuum welds in Examples 471, 474, 497 and 503. Usually, nonvacuum welds are smooth and do not need cosmetic passes (page 528).

Joint Design

Groove and melt-through electron beam welds are made on all basic joint types: butt, corner, T, lap and edge.

Most electron beam welds are square-groove or modified (usually rabbeted) square-groove welds on butt or corner joints (see Fig. 2 and 3); about 80% of the welds in the examples in this article are of this type.

Joints can be straight-line, irregular-outline, circumferential or circular joints. Circumferential and circular joints can be welded by rotating the work in the path of a stationary electron beam, as shown in Fig. 1.

Of the examples of electron beam welded joints in this article, 80% were circumferential or circular, with about the same number of each type.

Factors in Design. Many joints for electron beam welding have rabbeted grooves to make them self-aligning and at least partially self-fixturing, which is of particular importance in batch loading the vacuum chamber for efficient work manipulation.

Most joints are designed to be welded in a single pass with full penetration or penetration to a specified depth (see the section on Welding of Thick Metal, page 538, for the usual ranges of penetration). Depending on the application, welding may be preceded by a sealing pass or by tack welding, and be followed by a "cos-

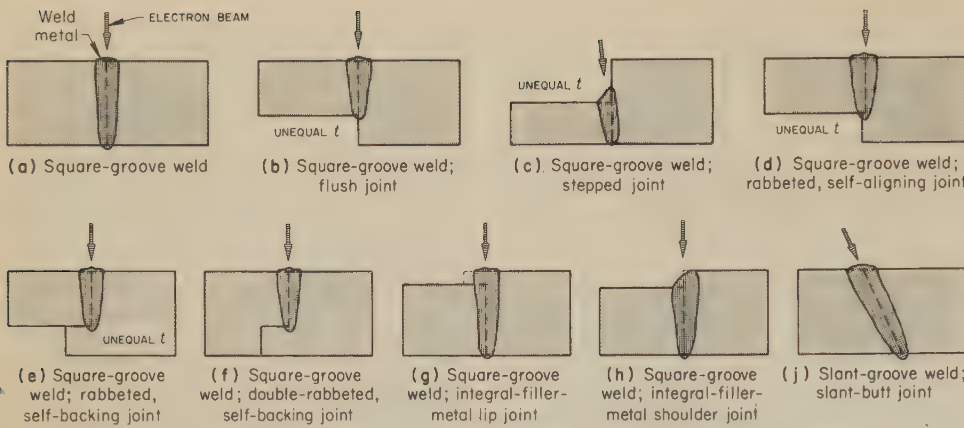


Fig. 2. Nine types of butt joints and welds used in electron beam welding

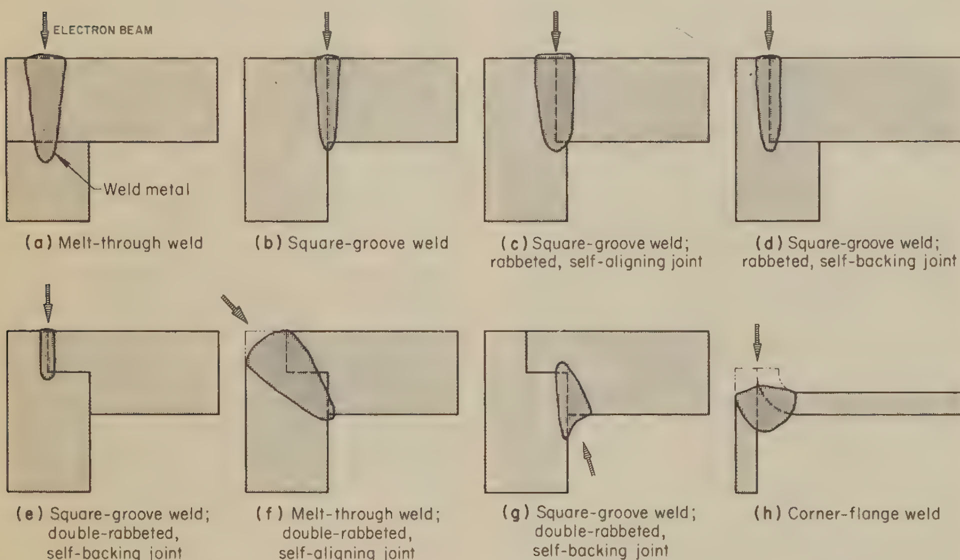


Fig. 3. Eight types of corner joints and welds used in electron beam welding

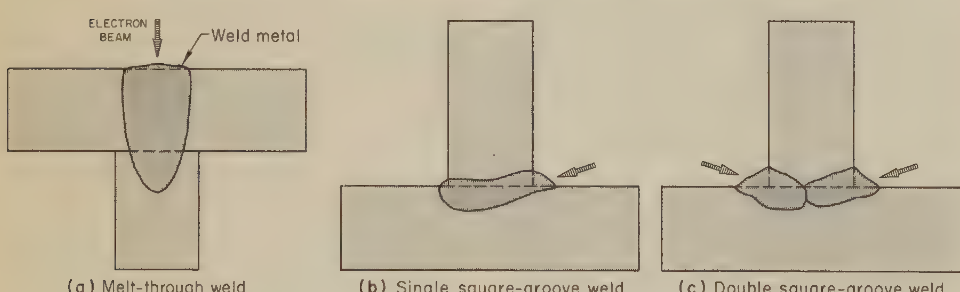


Fig. 4. Three types of electron beam welds in T-joints

metic" or smoothing pass. Most electron beam welds are continuous, but intermittent, spot and plug welds are also made. When filler metal is to be added in making an electron beam weld, either by preplacing wire or strips of filler metal in or at the joint, or by feeding filler-metal wire, a suitable root opening (or, sometimes, a groove bevel) is provided to permit convenient placement or feeding (see "Use of Filler Metal", page 539).

Special joint details are sometimes added to serve as thermal conduction barriers or as heat sinks, in making welds close to heat-sensitive locations in the workpieces. Integral backing or separate backing strips or rings are used to prevent spatter and loss of weld metal, to serve as heat sinks, or to avoid root defects in metal that will not be machined away after welding.

As with arc welding, joint strength, ductility, fatigue life, and avoidance of stress concentration must conform with service requirements.

Common Joint and Weld Types. Figures 2 to 6 show the commonly used joint and weld types for electron beam welding. Different joint preparations, joint designs and welding positions are used to meet special requirements.

Welds in Butt Joints

The basic square-groove weld, which is shown in Fig. 2(a), (b) and (c), needs only the simplest and least expensive joint preparation, and is suitable for either partial or full-penetration welds. Good fit-up and external fixtures are needed. The flush joint (Fig. 2b) is preferred to the stepped joint (Fig. 2c) for joining unequal thicknesses, chiefly because control of conditions for making sound full-penetration welds is less critical than for the stepped joint. A wider beam is used in welding the stepped joint, and the beam angle must be carefully controlled to avoid scarfing the upper edge of the thicker member (angle too small) or missing the bottom of the joint (angle too large), especially if the thinner member is more than about ⅜ in. thick.

Joint (d) in Fig. 2 is rabbeted to make it self-aligning, but the offset is small, to avoid leaving an unwelded seam near the root of the weld (compare Fig. 2e). Joints (d) to (g) in Fig. 2 are self-aligning and may be self-fixturing in circular, circumferential and certain other joint arrangements. Joints (e) and (f) are both self-aligning and self-backing; each, however, leaves an unwelded seam near the root of the weld.

Welds (g) and (h) in Fig. 2 show two ways of providing integral filler metal. The lip of joint (g) provides more filler metal than the shoulder of joint (h), but because it conceals the joint, a scribed line or other means for beam placement and for scanning must be provided before the welding operation can proceed.

The slant-groove weld (also called angular or scarf) shown in Fig. 2(j) is used in butt joints to facilitate fixturing, and where limitations on the beam location would prevent fusion for the entire groove depth if the basic square-groove weld (Fig. 2a) were used. Greater weld depth, as measured parallel to the beam axis, is needed for full penetration of a given work-metal thickness than with the square-groove weld. This type of weld and variations of it are used both in butt joints and in corner joints.

A slant-butt joint can also be welded with beam alignment set at 90° to the surface of the work. This beam angle will permit the production of defect-free welds where fit-up is poor or where the joint opening is larger than can be tolerated when the beam is aligned with the groove. In a related type of weld, the joint has a square-groove or modified square-groove preparation, and the beam is at an angle to the groove. The main reason for using this type of weld is difficulty of access with other types of welds, as in Example 469.

The use of slant-groove welds in circumferential butt joints is described in Examples 486 and 491 on pages 550 and 554, respectively, in this article.

Butt joints are the most common of the five basic joint types used in electron beam welding; about 60% of the electron beam welds described in examples in this article were in butt joints. In welding a flange to a tube, the use of a butt joint in the tube ("welding neck" construction) is preferred to the use of a corner joint, which would concentrate bending stresses at the weld (see Example 464).

Welds in Corner Joints

Eight types of electron beam welds frequently made in corner joints are shown in Fig. 3.

Corner joints are second only to butt joints in frequency of use for electron beam welding; about a fourth of the electron beam welds described in examples in this article were in corner joints. Most are welded from the outside; an inside corner weld is described in Example 499.

Important differences between butt and corner joints are notch sensitivity and suitability for nondestructive testing. (To compare alignment, self-fixturing, and the occurrence of portions of unwelded seam, see Fig. 2 and 3.)

The two simplest and most economical welds in corner joints are the melt-through (Fig. 3a) and basic square-groove (Fig. 3b) welds. Neither is self-aligning or self-fixturing; manipulation of the work for weld (b) in Fig. 3 can be simplified by using a horizontal electron beam and corresponding work orientation (rotated 90° from the orientation shown). The melt-through weld (Fig. 3a), unless made with a fusion zone wide enough to eliminate the unwelded seam completely, is weaker than the square-groove weld and is notch sensitive.

The corner-flange weld (Fig. 3h), usually made only on thin stock, requires precision forming of the 90° bend. Welds in corner joints are subject to high stress concentrations.

Welds in T-Joints

Three types of electron beam welds made in T-joints are shown in Fig. 4. The melt-through or blind weld (Fig. 4a), like melt-through welds in butt or corner joints, leaves an unwelded seam, with resulting low strength, notch sensitivity and corrosion susceptibility. The double square-groove weld (Fig. 4c) is used primarily on sections 1 in. or more in thickness. For types (b) and (c), filler metal is usually added.

Welds in Lap Joints

Three types of electron beam welds made in lap joints are shown in Fig. 5. They are most frequently used in joining thicknesses of about $1/16$ in. or less.

Both the melt-through (Fig. 5a) and the single fillet (Fig. 5b) welds leave an unwelded seam. The major application of a melt-through weld in lap joints is for metal 0.005 in. or less thick; a partially defocused beam or sinusoidal deflection transverse to the travel direction is used to increase weld width at the interface.

The single and double fillet welds (Fig. 5b and 5c) are made with a partially defocused beam to broaden the weld and provide a smooth transition. Especially on thick stock, filler metal may be added to increase fillet size.

Examples 490, 498 and 502 describe electron beam welds in lap joints.

Welds in Edge Joints

Three types of electron beam welds made in edge joints are shown in Fig. 6. Thick sections can be joined by deep, narrow square-groove welds (Fig. 6a). Shallow welds made with a low-power, partially defocused beam are used to join thin sections to each other or to thick sections, as shown in Fig. 6(b) and (c). Shallow edge welds can be made at high speed. Welds of this type are particularly useful on hermetically sealed assemblies, which may be designed for planned salvage by removal of the weld region and subsequent rewelding.

Electron beam welds on edge joints are described in Examples 478, 482, 485 and 501 in this article.

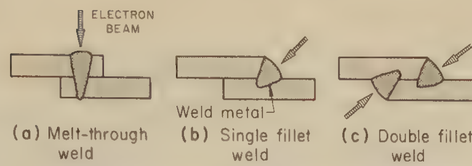


Fig. 5. Three types of electron beam welds in lap joints

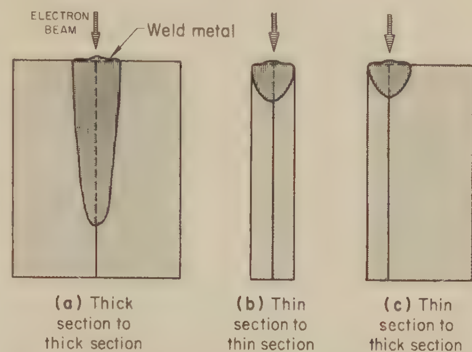


Fig. 6. Three types of electron beam welds in edge joints between members of similar or different section thicknesses

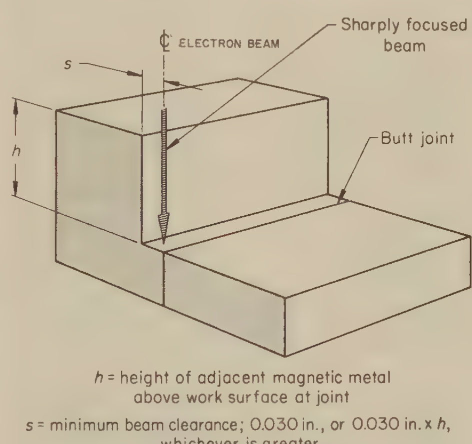


Fig. 7. Joint location and beam clearance for a butt joint near a projecting corner, T or shoulder in a magnetic work metal. For electron beam welding of a straight-line joint of cross section as shown, or a circular or circumferential joint.

Butt vs Corner and T-Joints

The concentration of bending stresses at the weld in corner and T-joints is sometimes avoided by designing the work for a butt joint on a straight section near the corner or T (flange-neck or welding-neck construction). This principle of design is applicable also to butt joints between members having different thicknesses, and it can be applied to straight-line, circular and circumferential joints. Its use is illustrated in Example 464.

In welding such a joint in magnetic metals, if the beam path is too close to the corner, T or shoulder, the beam may be deflected away from the metal that it passes near on its way to the joint, causing it to enter the work at an angle and possibly to miss the lower portion of the joint. To avoid this, the beam clearance should be 0.030 in. or more, depending on the height of the magnetic projection (Fig. 7).

Special Joints and Welds

Many variations of the basic joint and weld types described in the preceding section and illustrated in Fig. 2 to 6 are used to meet the needs of individual applications. Some of these special joints and welds are discussed in the following paragraphs.

Plug and puddle welds are usually made with manual manipulation of the work under a fixed beam at low power. Filler metal used for plug welds is often preplaced at the weld site. Puddle welding is used mainly to fuse shallow defects together locally.

Multiple-Pass Welds. Most electron beam welds produce the desired penetration in a single pass. (Tack welds and cosmetic or smoothing passes are not considered penetration passes.) Welds several inches deep can be made in most metals in a single pass (see the section on Welding of Thick Metal, on page 538). Weld depth obtainable in a single pass can be nearly doubled by welding from both the face and the back of the work, as was done in Example 478, in which weld passes 3 in. deep were made from opposite sides for a full penetration of $5\frac{3}{8}$ in.

In a variation on straight-through two-pass welding from opposite sides, separate welds that meet, or almost meet, can be made at an angle of 90° to each other in a rabbeted square-groove joint, as in Example 488.

Tangent-tube welds are longitudinal welds joining two parallel tangent tubes (or cylinders). The tubes may differ in size; the beam is perpendicular, or nearly perpendicular, to the common axial plane of the two tubes. Added filler metal may be used for reinforcement. Thinner-wall tubes can be joined than by arc welding.

Three-Piece Welds. Welds that join three or more pieces in which there is penetration in a single pass into all of the pieces can be made. Many of the difficulties encountered in welding very thin metal or foil are eliminated by sandwiching it between two thicker sections, as in the melt-through welding of 0.002-in.-thick stainless steel in Example 476. Special types of joints are described in Examples 469 and 473.

Transition joints ordinarily are made with two or more separated welds. An unusual transition-joint design, which was used in welding 1113 steel to 2024-T4 aluminum, is shown in Fig. 53.

Multiple-tier welds are welds made simultaneously in in-line, separated joints (usually butt joints) in a single pass of the electron beam. A more detailed discussion is given in the section on Multiple-Tier Welding, page 541.

Welds using integral filler metal may be of the types shown in Fig. 2(g) and (h), in which an overhanging lip or a shoulder provides filler metal to a butt joint, or both members may be made thicker at the joint than elsewhere.

Examples 464, 465, 480, 484, 487 and 489 in this article describe joints that provided integral filler metal.

Joint Design in Examples of Practice

In addition to those already cited, other examples of practice in this article show various important aspects of joint design.

Heating was minimized in Example 501 by machining slots on either side of the weld groove, which reduced both the amount of heat needed and heat transfer to nearby sensitive components (for a given heat input). This design, which allows slight yielding under shrinkage stress during cooling, thus lowering residual stress, has often been used to make welds that could not otherwise be made. In Examples 465 and 475, the cross section of one member was reduced next to the joint to impede heat transfer.

In Example 487, a ring that was to be welded to a shell was made extra thick to permit welding to a depth sufficient to put any voids near the weld root in a region that would be machined away after welding.

The design of joints between thin and thick sections so that the thick member of the joint provides a heat-sink effect to prevent melting of the thin member is discussed in the section on Welding of Thin Metal, page 536.

The two examples that follow illustrate several aspects of joint design.

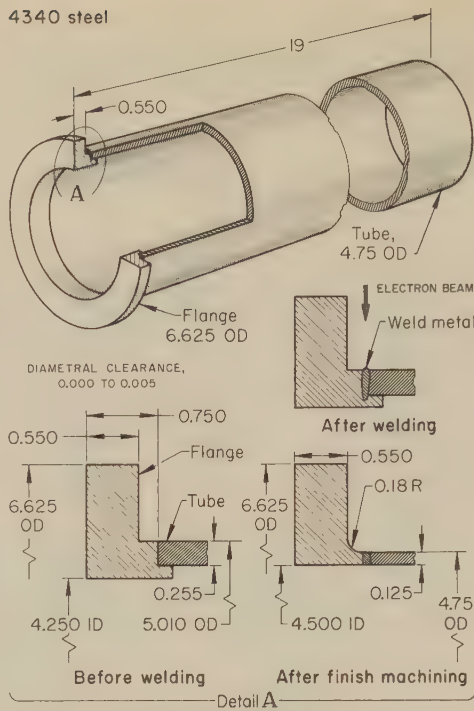
Example 464. Use of an Oversize, Self-Aligning, Self-Backing Butt Joint in a High-Strength Flange-to-Tube Weld on 4340 Steel (Fig. 8)

Joint design was critical in the carefully planned and executed procedure used to produce a flange-to-tube assembly of 4340 steel for an aircraft engine mount. Basically, the procedure consisted of welding an oversize assembly and then machining to finished dimensions, as indicated in detail A of Fig. 8. Process selection, fixturing, welding, heat treatment, inspection and final machining were also important to the success of the application.

Process Selection. Electron beam welding was selected primarily to obtain deep, narrow welds at high speed with low total heat input, for high strength. Tests had shown that high joint efficiencies were obtained in static tensile and fatigue loading. In addition, electron beam welding produced low distortion, and provided excellent control of penetration.

Fusion under a high vacuum promoted weld cleanness, as determined by x-ray radiography. Very clean welds could be obtained by using a vacuum-melted steel; in this application, however, air-melted 4340 steel was used.

Joint Design. The type of butt joint used is shown in detail A of Fig. 8. The normalized, seamless 4340 steel tubing was finish machined on the inside and rough machined on the outside. The flange was of welding-neck design, which located the weld away from major flange bending stresses and simplified nondestructive inspection. The outside of the flange hub was rough machined to the outside diameter of the tube, and the inside diameter of the hub was machined ¼ in. undersize.



Joint type	Circumferential butt; self-backing
Weld type	Square groove
Weld depth-to-width ratio (typ)	3.7
Machine capacity	150 kv at 40 ma
Gun type	Pierce; fixed
Vacuum-chamber size	56 by 56 by 108 in.
Fixtures	Lathe-type positioner with plug and face plate; rotary indexing table
Preheat	None
Welding power	130 kv at 24 ma
Welding vacuum	Less than 10^{-4} torr
Beam focal point	0.250 in. above work surface
Welding speed	31.4 ipm (2 rpm)
Weld time	30 sec
Production rate	12 pieces (one load) per hour
Postheat	Stress relieve (950 F for ½ hr); quench and temper to a tensile strength of 150,000 to 172,000 psi (see text)

Fig. 8. Flange-to-tube assembly that was precision welded for a critical application, using an oversize, self-aligning, self-backing butt joint and controlled penetration (Example 464)

The overlapping lip, made by cutting a recess in the hub, served for alignment and weld backing. The lip was sufficiently thick (0.125 in.) to permit controlled-penetration welding beyond the inside diameter of the tube, so that any root voids would be in the region to be machined away after welding and so that there would be no weld spatter on the interior of the tube. Diametral clearance was zero to 0.005 in., for accurate axial alignment.

Joints were cleaned by vapor degreasing and wiping with acetone. The parts were then demagnetized and assembled.

Fixturing. To permit welding in the horizontal-rolled pipe position, a lathe-type positioner was used. With a plug at the tailstock to fit the tube and a face plate at the headstock aligned by three tooling holes in the flange face, the joint was precisely located for rotation under the electron beam gun. Fit-up tolerances, including mismatch, were held within 0.005 in. Fixtures were vented to prevent any buildup of air pressure in the tube during welding.

By mounting the fixtured assemblies on a rotary-indexing fixture, a batch of 12 assemblies could be welded in one hour during one pumpdown. All fixtures were made of nonmagnetic stainless steel.

Welding. Machine settings for the welding operation were determined on test pieces, to obtain a fusion pass that would penetrate the joint up to 60 to 70% of the backing-lip thickness. Partial penetration, as shown in detail A of Fig. 8, eliminated the possibility of weld spatter damaging the interior of the tube. The table with Fig. 8 summarizes machine settings and other welding conditions. During weld starting and stopping, beam energy was regulated by upslope and downslope current control, which made necessary slightly more than one full revolution of the work to complete the weld.

Heat Treatment. Immediately after a batch was welded, the parts were stress relieved at 950 F for ½ hr, and heat treated to a tensile strength of 150,000 to 172,000 psi, by heating to 1550 F for 1 hr, quenching, and tempering at 1250 F for 2 hr.

Inspection. Before final machining, all welds were inspected visually and by magnetic-particle testing. After final machining, the joints were inspected by radiographic and ultrasonic examination. Acceptable defects were limited to 5% of minimum thickness, or approximately 0.006 to 0.007 in. in size.

Final Machining. The flange was rebored to the same inside diameter as the tube. The outside tube surface and the flange hub were machined to finished wall thickness, as shown in detail A of Fig. 8. Roughness was held to 63 micro-in., and tolerances required concentricity over the tube length within 0.005 in.

Example 465. Joint Design, Equipment and Procedure for Welding Controlled-Strength Joints Between 8620 Steel and GMR-235 at a High Production Rate (Fig. 9)

Supercharger impellers for diesel engines were produced in batches of 24 by electron beam welding. A typical impeller, as shown in Fig. 9, was made by welding a shaft of vacuum degassed, nonleaded 8620 steel bar to a wheel hub of cast nickel-base alloy GMR-235 (8 to 12 Fe, 14 to 17 Cr, 4.5 to 6 Mo, 2 Ti, 2.5 to 3.5 Al, 0.15 C, rem Ni).

Before welding, shaft bearing surfaces were carburized, and the shaft was hardened and tempered. The objective was to obtain consistent joints of high weld integrity with low distortion. Concentricity requirements on machined bearing surfaces were 0.005-in. TIR after welding.

Joint design used was basic to the welding operation and to the end use of the part. Because the wheel was to be exposed to high temperatures, the joint was made at the end of an annular hub to provide a heat barrier. The depth of the joint provided a weld of sufficient strength for normal operation, but also of relative weakness, so that, if a seizure took place, the unit would rupture in this location and in this way prevent more extensive damage.

A small chamfer was cut on the inside edge of the joint (joint detail, Fig. 9) to facilitate x-ray inspection. Complete joint penetration caused the chamfer to be filled; incomplete penetration was indicated by a void line on the radiograph.

A rabbeted, self-aligning, self-backing joint preparation was used, as shown in Fig. 9. The joint was designed with a small diametral clearance of 0.007 to 0.017 in., to permit a sliding fit, so that abutting joint surfaces could be held together by the fixtures with uniform end pressure, to prevent blowout (expulsion of metal from the joint) during welding. A tack weld was made at 180° from the starting point.

Fixturing consisted of two 24-spindle rotating positioners, each spindle being separately spring-loaded to provide constant axial pressure on each joint before, during and after welding, regardless of the slight expansion and contraction that occurred. While one batch of 24 units was being welded in sequence, a second batch was being fixtured to avoid loss of machine time.

Welding Equipment. The principal features of the electron beam welding machine adapted to this operation were:

1 A relatively large vacuum chamber (30 by 36 by 24 in. deep) capable of handling the 24-unit fixtures
2 A movable electron beam gun capable of travel from one unit to the next during one vacuum pumpdown

3 A vacuum pumping system capable of relatively fast pumpdown
4 An observation system that would permit accurate beam alignment and continual monitoring of the complete welding operation on the 24-piece load. The beam was aligned with a 20-power telescope mounted outside the chamber. The chamber was also fitted with three glass viewing ports 18 in. in diameter, located at 90° with respect to each other, for oblique viewing with the unaided eye.

Observation of the complete operation was important during both initial setup and production welding. During initial setup, it was used to observe the effects of varying techniques and machine settings, in determining optimum welding conditions. During production, it was used to detect, as soon as possible, any deviations in the operation. Optical surfaces that were directly exposed to the operation required frequent cleaning because of metal-vapor deposition.

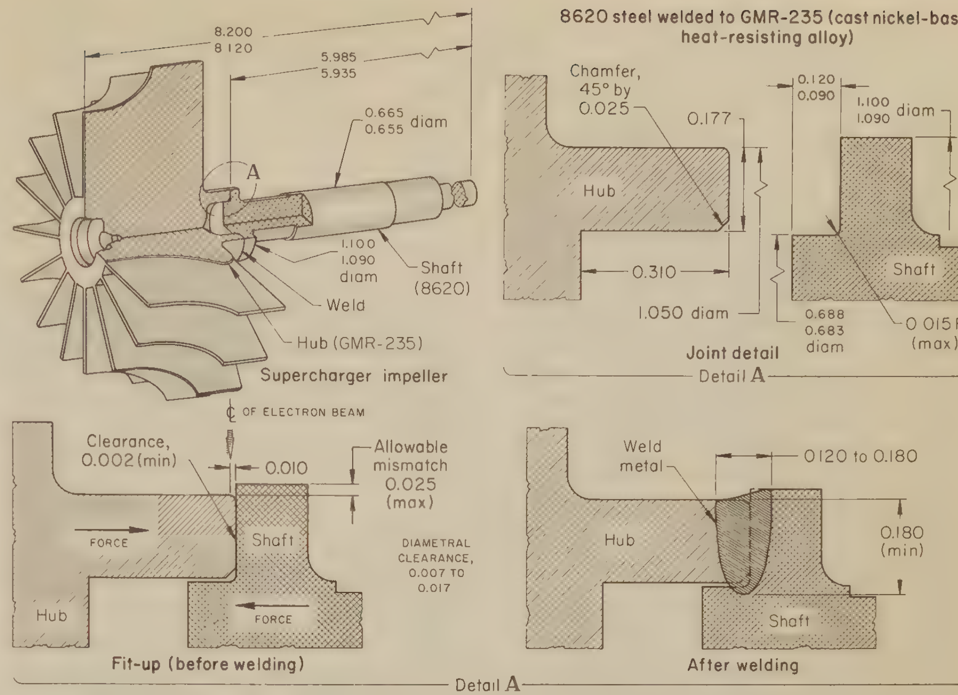
Welding Technique. The welding procedure was one often used in welding dissimilar metals. Cracking and porosity were controlled by directing the beam about 0.010 in. off the joint on the side of the GMR-235 component. Because this affected the relative amount of melting of each alloy, the beam focal point was set at the midsection of the joint, making the beam wider at the joint surface. To suit these conditions, a relatively low welding speed was used. The wide beam and low speed aided in accurate indexing of successive parts.

This type of beam alignment and focus required careful fitting of the abutting joint surfaces. If the joints were not tightly closed, blowouts occurred, with attendant loss of concentricity, and with undercutting and porosity. Careful fit-up was accomplished by adjusting the spring tension on the spindles of the fixture.

Weld quality was also affected by the alignment of the beam with respect to the axis of the part. Variations in alignment could be observed through the port facing the axial direction, and corrections could be made as needed.

The part was welded automatically in one pass. Current downslope was automatically started at overlap and continued to taper out over a 120° arc. Beam oscillation was not used.

Details of the equipment, machine settings, and welding conditions are given in the table with Fig. 9.



Joint type	Circumferential butt; rabbeted, self-aligning, self-backing	Welding vacuum	10^{-4} torr
Weld type	Square groove	Pumpdown time	8 min(b)
Machine capacity	60 kv at 500 ma	Beam spot size	0.040-in. diameter
Gun type	Pierce; movable; square filament	Beam focal point	At midjoint depth
Maximum vacuum	5×10^{-6} torr	Working distance	2.5 in.
Fixtures	24 unit, multiple spindle, spring loaded(a)	Welding speed	14.5 ipm
Welding power	26.5 kv at 52 to 54 ma	Number of passes	One, plus 120° downslope
		Production rate	80 parts per hour(c)

(a) Two fixtures; one was being loaded while the other was being used. (b) Pumpdown time for a fully loaded chamber. Time for an empty chamber was about 4 min. (c) From loading to unloading of a batch of 24 units; based on a 50-min hour.

Fig. 9. Supercharger impeller that was made by electron beam welding of a shaft and a wheel of dissimilar metals. Joint design, operating conditions, and equipment selection were important for meeting end-use requirements at a high welding rate. (Example 465)

Welding in High Vacuum

Much electron beam welding is done in a vacuum chamber in which the pressure is held at a maximum of 10^{-4} torr. Maintenance of this high vacuum has important effects on the electron beam and on the properties of the weld and the heat-affected zone.

Effect of Pressure on Beam. In a high vacuum, the electron beam undergoes very little scattering from collisions with gas molecules. The frequency of such collisions is roughly proportional to the concentration of gas molecules in the vacuum chamber. For work-chamber pressures encountered in electron beam welding, the number of gas molecules present in a cube 0.001 in. on a side (a volume of 10^{-9} cu in.) and the corresponding relative frequency of collisions with the electrons are as follows:

Pressure, torr	Number of molecules	Relative frequency of collisions
10^{-5}	5,800	1
10^{-3}	580,000	100
10^{-1}	58,000,000	10,000
760	4.4×10^{11}	100,000,000

At pressures of 10^{-4} torr or less, the beam can be held in sharp focus over a distance of several feet, depending mainly on the characteristics of the electron gun and the electromagnetic focusing system, for maximum effectiveness in producing deep, narrow welds. Beam scattering by collision with gas molecules begins to be significant at a pressure of about 10^{-3} torr, resulting in lower penetration and greater weld width at a given working distance and in shorter maximum working distances (see the section on Welding in Medium Vacuum). At atmospheric pressure (760 torr), the beam is so scattered in traveling about 6 in. as to become completely ineffective for welding. Hence, penetration and working distances for welding at atmospheric pressure are much lower than for welding in high or medium vacuum.

Effect of Pressure on Weld and Heat-Affected Zone. The maintenance of a high vacuum in the work chamber protects the weld metal and the heat-affected zone from oxidation and contamination by harmful gases, serving the same function as inert shielding gases do in arc welding, while also degassing the weld. The contamination level as a function of pressure is discussed in the section "Welding in Medium Vacuum", on the next page.

The nearly complete absence of gaseous impurities eliminates the serious contamination difficulties that are usually encountered when attempting to arc weld reactive metals such as titanium and zirconium.

Width of Weld and Heat-Affected Zone. Electron beam welds made in a high vacuum are narrower and have narrower heat-affected zones than comparable welds made in medium vacuum or at atmospheric pressure, and they are much narrower than the narrowest welds made in production welding by the gas tungsten-arc process. The narrow width of the tempered zone in hardenable steels and other hardenable alloys permits welding of these metals after heat treatment, in many instances without loss of strength (see Fig. 38 and 39).

Limitations. A major limitation in the use of high vacuum in the work chamber is the effect on unit production time, because of the need to pump the chamber down before each load is welded. Pumpdown time is typically about 3 min for a 30-cu-ft chamber and 10 min for a 300-cu-ft chamber. The above pumpdown times are realistic only for a very clean and well-maintained system. In production, pumpdown will often be nearly double the above times.

The effect of this limitation on unit production time is reduced by welding a number of assemblies in each load and by keeping chamber size as small as possible. Small chambers specially designed for use with small workpieces have typical pumpdown times of 1 min (225-cu-in. chamber) and 15 sec or less (60-cu-in. chamber).

A second major limitation in the use of high vacuum is that work size is limited by chamber dimensions. This limitation is sometimes circumvented by the use of a chamber having special openings and seals that permit oversize work to extend outside the chamber, or by the use of a portable clamp-on chamber.

Welding Conditions. Welding in high vacuum is done with low-voltage, as well as high-voltage, equipment. Except for the sections specifically covering medium-vacuum and nonvacuum welding, this article deals primarily with high-vacuum welding. Of the 42 production examples of electron beam welding, 37 describe welding in high vacuum, and the actual welding conditions used on specific parts are given and the critical variables are discussed for each example.

Beam voltage in these 37 examples is 15 to 150 kv; beam current, 2 to 170 ma; and welding speed, 14 to 119 in. per minute (except for Example 485, in which manual guidance along the seam required welding at a speed of 2 to 3 in. per minute).

The energy input to the work needed to produce a weld of the required depth of penetration and width is the basis for selecting the welding conditions.

Depth of penetration is increased by increasing the voltage or current for greater beam power, or by decreasing the welding speed. Table 1 lists approximate energy inputs per inch of weld length for making narrow single-pass electron beam welds 0.25 to 3 in. deep in the weldable alloys of copper, iron, nickel, aluminum and magnesium. These values are intended to serve as starting points for establishing conditions for welding work for which no previous experience is available. Energy-input requirements for specific applications depend on the alloy composition and special operating conditions such as the use of beam oscillation or a defocused beam.

Table 1. Energy Input at the Weld for Single-Pass Electron Beam Welding in High Vacuum for Various Depths of Penetration (a)

Depth of penetration, in.	Kilojoules per inch of weld length for welding alloys of: Cu	Fe	Ni	Al	Mg
0.25	7	5	4	2	1
0.50	15	10	8	5	3
0.75	25	18	15	8	5
1.00	37	27	22	13	8
1.50	62	46	39	23	15
2.00	87	68	60	35	22
2.50	112	90	80	47	29
3.00	137	112	100	59	36

(a) Values are approximate and apply to the commonly welded alloys of the metals. They are intended to serve as starting points for establishing conditions for making narrow welds. Energy input may vary substantially from these values in specific applications, depending on the composition of the alloy and special operating conditions (see text). Energy input at weld (kilojoules per inch of weld length) = beam voltage (kv) × beam current (ma) × 0.06 ÷ welding speed (inches per minute).

Welding in Medium Vacuum

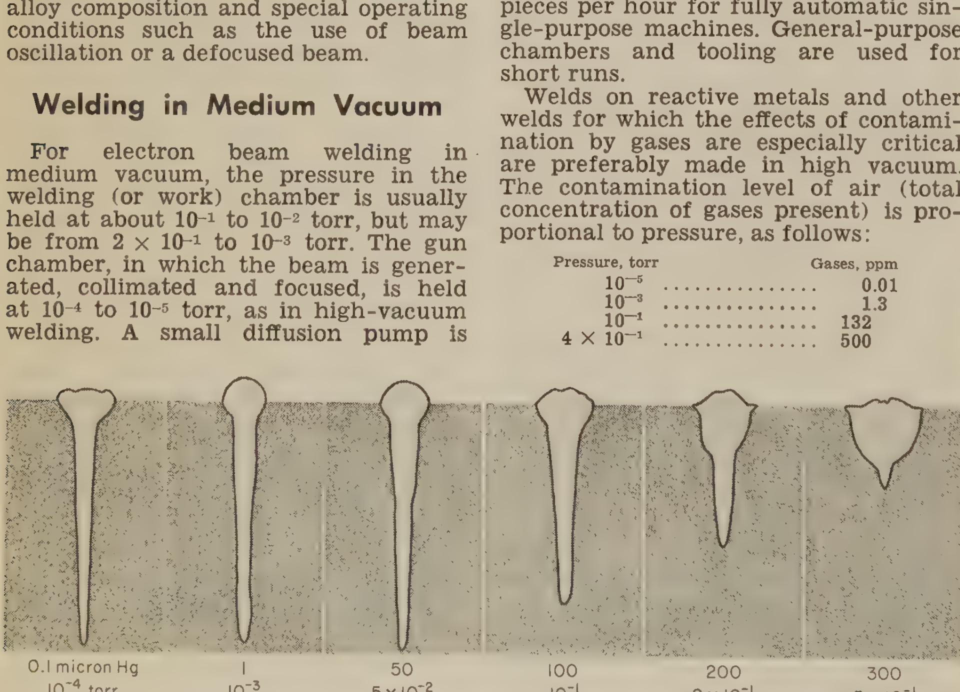
For electron beam welding in medium vacuum, the pressure in the welding (or work) chamber is usually held at about 10^{-1} to 10^{-2} torr, but may be from 2×10^{-1} to 10^{-3} torr. The gun chamber, in which the beam is generated, collimated and focused, is held at 10^{-4} to 10^{-5} torr, as in high-vacuum welding. A small diffusion pump is needed to provide the vacuum in the gun chamber, but a diffusion pump is not needed for pumping down the welding chamber, which can be evacuated with a mechanical pump.

Comparison With High-Vacuum Welding. The chief advantage of welding in medium vacuum, compared with welding in high vacuum, is the short pumpdown time for the welding chamber, which ordinarily does not exceed 40 sec for a general-purpose chamber (of about 4 cu ft), and which is less than 5 sec for the specially designed chambers used in welding small parts. Accordingly, medium-vacuum welding permits mass production of parts, using a chamber of minimum volume.

Production rates for welding in medium vacuum depend on part design and other factors; maximum production rate is typically about 50 pieces per hour for manual equipment, 500 pieces per hour for specially tooled semiautomatic machines, and 1500 pieces per hour for fully automatic single-purpose machines. General-purpose chambers and tooling are used for short runs.

Welds on reactive metals and other welds for which the effects of contamination by gases are especially critical are preferably made in high vacuum. The contamination level of air (total concentration of gases present) is proportional to pressure, as follows:

Pressure, torr	Gases, ppm
10^{-5}	0.01
10^{-3}	1.3
10^{-1}	132
4×10^{-1}	500



For electron beam welds made on type 304 stainless steel, using a beam length of 16 in. without changing focus. Maximum penetration shown is approximately ½ in. Welding conditions were: 150 kv, 30 ma, and 60 in. per minute. (J. W. Meier, *Metal Progress*, July 1966, p 63-64)

Fig. 10. Effect of welding-chamber pressure on penetration and weld shape

Lower contamination levels are obtainable than those actually observed for arc welding with inert-gas shielding.

Penetration and Weld Shape. Penetration at a given power level is ordinarily 5 to 10% less than for high-vacuum welding, and welds are wider and slightly more tapered. These changes are caused by the scattering of the electrons in the beam by collision with gas molecules, which makes the beam broader.

The effect of welding-chamber pressure on penetration and weld shape is shown in Fig. 10 for welds made on type 304 stainless steel, using a beam length of 16 in. Penetration drops off rapidly at pressures of 10^{-1} torr or more at this beam length, and at somewhat lower pressures when the beam path is longer.

Comparison With Nonvacuum Welding. Disadvantages of medium-vacuum welding, compared with welding at atmospheric pressure, are the limitations on work size imposed by the need to enclose the work in a vacuum chamber and the time needed for chamber pumpdown.

Beam deflection and oscillation, which cannot be used in welding at atmospheric pressure, can be used in medium-vacuum welding.

Applications of Medium-Vacuum Welding. Most parts that can be welded in high vacuum can also be welded in medium vacuum. Depth of penetration is less than in high-vacuum welding, and depth-to-width ratio is less than about 10 to 1. Reactive metals are less readily welded in medium vacuum than in high vacuum.

Medium-vacuum welding has been used for welding mass-produced automobile parts, such as gears and shafts, that are welded to close tolerances and are not subsequently finished. The examples of medium-vacuum welding in this article involve steel or stainless steel parts made in small and intermediate quantities.

For instance, in Example 472, transmission gears made of 8620 steel were assembled by ¼-in.-deep medium-vacuum electron beam welds that had a maximum width of 1/16 in. Arc welding processes could not provide an acceptable weld depth-to-width ratio and caused distortion and melting through.

In Example 487, an assembly of a flange to a housing, both made of 52100 steel, was welded at a production rate of 10 pieces per hour. The production rate could readily have been increased to about 40 assemblies per hour if the production quantity had been large enough to justify more efficient work-handling equipment.

In the example that follows, medium-vacuum electron beam welding at a pressure of 5×10^{-2} torr replaced gas metal-arc welding that had excessive labor-time requirements and high filler-metal consumption in joining thick type 410 stainless steel turbine blades.

Example 466. Change From Gas Metal-Arc Welding to Medium-Vacuum Electron Beam Welding To Reduce Labor Time and Cost (Fig. 11)

Steam-turbine diaphragms (stators), ranging from 3 to 12 ft in diameter and from 1 to 2½ in. in thickness, were produced by welding together the more than

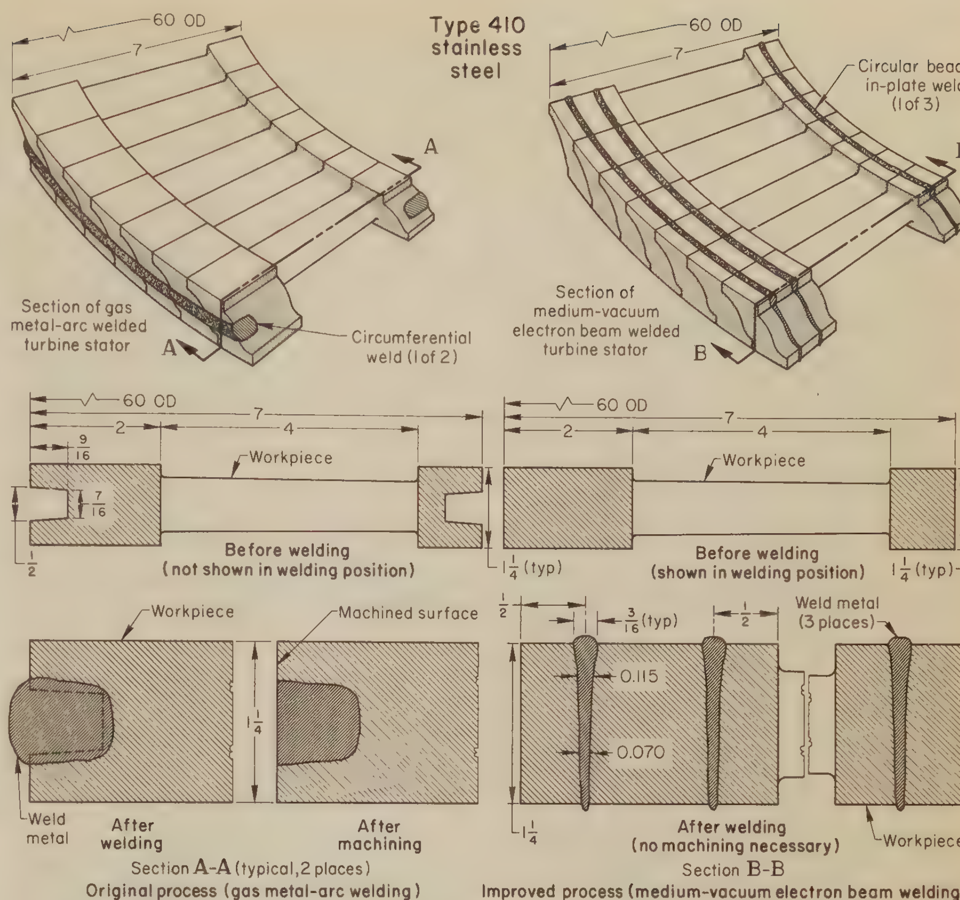
100 separate blades that formed the disk. Automatic gas metal-arc welding had been used satisfactorily, but when electron beam welding was investigated, it was found that labor time and cost could be reduced.

Medium-vacuum electron beam welding was selected to replace the arc welding procedure. Out-of-chamber (nonvacuum) welding would have been ideal because of the large diameter of the diaphragms, but the process was limited to metal thicknesses less than ⅝ in. High-vacuum electron beam welding could easily have met the welding requirements, but the cost probably would have been higher and the large chamber needed would have necessitated long pumpdown times. The medium-vacuum method provided adequate weld quality, full penetration, and short pumpdown time. Welds had a depth-to-width ratio of 6.7 to 1.

A sector of a typical diaphragm, made of 410 stainless steel, is shown schematically in Fig. 11, broken at a joint between blades to show the type of weld made by each process. The function of the welds was to join the blades into an integral disk that would minimize vibration and reduce steam leakage.

The differences between the two welding procedures were substantial (see the list of operations with Fig. 11). For gas metal-arc welding, diaphragms were fixtured and set up in a boring mill and machined to form the inside and outside weld grooves. After setting up for automatic welding, still in the same fixture, the part was torch preheated to 500 F to minimize distortion and prevent cracking in the heat-affected zone. The grooves were filled by multiple-pass welding, using a $\frac{3}{32}$-in.-diam ER410 electrode. After welding, diaphragms were returned to the boring mill, where the welds were faced flush.

In contrast, electron beam welding required no preheat, no machining, and no filler metal, and welding time was reduced about 90%. Preweld cleaning consisted of degreasing. A summary of the average time for welding and related operations for a diaphragm of the size shown in Fig. 11 is given in the table with the illustration. Details of the electron beam welding procedure that replaced the gas metal-arc welding process are also given.



Operation	Gas metal-arc welding	Electron beam welding
Assembling blades in fixture	2 hr	2 hr
Machining weld grooves	4	0
Preweld cleaning	0	1
Setting up for welding(a)	1	1
Preheating	2	0
Welding, inspecting, and repairing	6	0.75
Machining weld faces	2	0
Total time for welding and related operations	17 hr	4.75 hr

Conditions for Medium-Vacuum Electron Beam Welding

Joint type	Special (see sketch)
Weld type	Bead in plate (no groove)
Machine capacity	150 kv at 176 ma
Gun type	Fixed
Vacuum-chamber size	150 by 54 by 180 in.
Maximum vacuum	10^{-2} torr
Fixtures	Holding jig; turntable
Welding power	130 kv at 90 ma
Welding vacuum	5×10^{-2} torr
Working distance	30 in.
Beam focal point	¼ in. below work surface
Beam spot size	⅛-in. diameter
Beam oscillation	None
Welding speed	12 ipm (approx)
Pumpdown time	7 min

(a) Includes pumpdown time for electron beam welding

Fig. 11. Sections of a turbine diaphragm (stator) for which electron beam welding replaced gas metal-arc welding for joining the blades. Process change eliminated preheating and two machining operations, and reduced welding time. (Example 466)

Nonvacuum (Out-of-Chamber) Welding

In nonvacuum, or out-of-chamber, electron beam welding, the work to be welded is not enclosed in a vacuum chamber; it is welded at atmospheric pressure. The electron beam is generated at high vacuum, as for high-vacuum and medium-vacuum welding, and is passed through a beam transfer column, exiting through a small orifice to the atmosphere. The beam transfer column consists of several distinct pumping chambers that are separated by small orifices and maintained at progressively higher pressure levels from the electron emitter to the exit. The equipment is described in more detail on page 530.

The chief reason for using nonvacuum electron beam welding instead of high or medium-vacuum electron beam welding is that production rates are much higher and costs are lower, because no vacuum chamber is needed for the work and time is not consumed in pumping down for each load. In addition, work size is not limited by chamber dimensions. These advantages are gained at the expense of reduced penetration depth and working distance, thus imposing limits on the thickness and shape of work on which the nonvacuum method can be used. Also, out-of-chamber welds cannot be made as narrow and nontapering as welds made in a vacuum.

Nearly all metals that are arc welded, or electron beam welded in a vacuum, can be nonvacuum electron beam welded. Inert-gas shielding of the weld zone is provided when the molten weld metal or the heat-affected zone cannot be exposed to air. On readily welded metals, weld properties approach those of welds made in a vacuum; on difficult-to-weld metals, weld properties are usually lower than those of welds made in a vacuum.

Operating Conditions. The operating conditions for nonvacuum welding differ substantially from those for welding in high or medium vacuum. Beam dispersion increases approximately in proportion to the pressure, and the beam in nonvacuum welding would typically become so dispersed in traveling a distance of about 6 in. in air at atmospheric pressure as to be completely ineffective for welding.

To provide an electron beam of sufficient velocity to offset the scattering effect of collisions with gas molecules in the beam transfer column and the space between the end of the electron gun and the work, voltage is held constant at a high value — in the range of 100 to 175 kv — and the working distance (gun-to-work distance, as measured from the exit orifice) is kept as low as possible. This distance is often ¼ in. or less, and it is usually not greater than about ¾ in.

With voltage held constant, beam current, working distance, and welding speed are selected to provide the

Table 2. Speeds for Nonvacuum Full-Penetration Welding of Carbon and Low-Alloy Steel Pipe at a Beam Power of 12 Kw

Wall thickness, in.	Welding speeds, ipm In air	Welding speeds, ipm In helium	Relative welding speed in helium(a)
0.050	417	900	2.16
0.080	241	528	2.20
0.100	187	412	2.21
0.150	118	264	2.24

(a) Based on welding speed in air as 1.00

required penetration and weld shape for a sound weld. Because it is usually desirable to keep working distance as short as possible and welding speed high, beam current is the primary control variable in nonvacuum welding.

The small size of the exit orifice on the electron gun makes it necessary to focus the beam at or very close to the exit orifice. Accordingly, it is not possible to vary weld characteristics to a significant degree by changing focus. Similarly, beam deflection and oscillation are not possible. The absence of these adjustment capabilities in nonvacuum welding is not a handicap, because beam width is ordinarily great enough so that it does not promote undercut or porosity at the root of the electron beam weld.

A cosmetic pass is seldom needed on electron beam welds made at atmospheric pressure, because a smooth crown is produced on welds in most metals. The smoothness of the crown also improves the ease of nondestructive inspection of the as-welded surface; wire brushing is often adequate preparation for radiographic or dye-penetrant inspection.

The limitation on workpiece shape imposed by the need for a short working distance can be overcome to some degree by the use of electron gun nozzles specially designed to extend into restricted spaces. For instance, a special nozzle was used in making precision circumferential welds at the bottom of 0.070-in.-wide slots ¼ in. deep on a 1¼-in.-diam round shaft in one production nonvacuum application.

Filler metal is not ordinarily used except where necessary for weld reinforcement, to produce the desired weld properties, or to avoid cracking, as in Example 468.

A stream of dry filtered air, or an inert shielding gas such as argon or helium, is passed across the weld region in the space between the work and the electron gun, or may be supplied through a special insert-type nozzle assembly that is part of the exit orifice and is designed to minimize entrance of welding vapors and other contaminants into the gun. Auxiliary inert-gas shielding is supplied where needed for complete protection of the molten weld metal and the heat-affected zone from gaseous contaminants. Welds are sometimes made on carbon and alloy steel, and other readily weldable metals, without using shielding gas, as in Example 467.

However, shielding gas is often used; helium is the preferred gas. Weld shape can be changed by varying the flow of helium.

Penetration. Nonvacuum electron beam welds in production applications are seldom deeper than about ½ in.

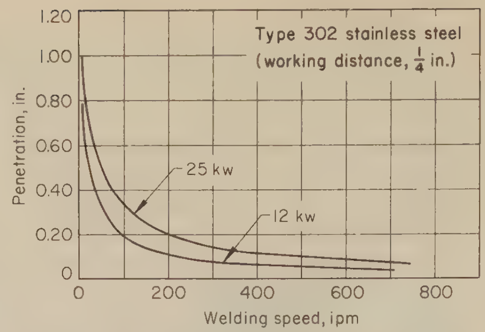


Fig. 12. Effect of welding speed on penetration for welding steel in air at atmospheric pressure, at a beam power of 12 and 25 kw and a working distance of ¼ in.

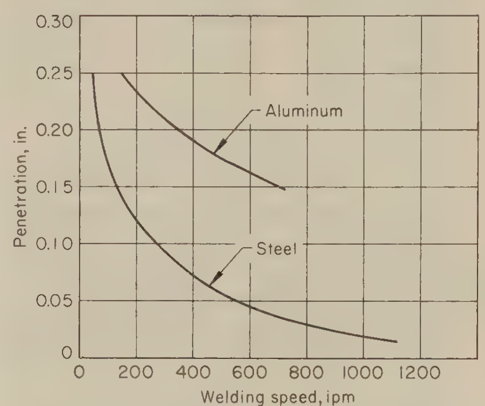


Fig. 13. Effect of welding speed on penetration for welding steel and aluminum in helium shielding gas at atmospheric pressure, using a beam power of 9 kw

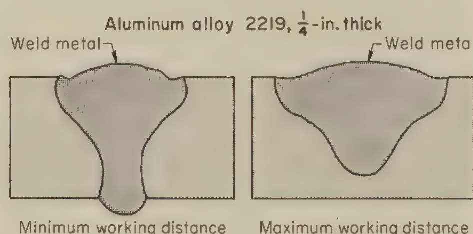


Fig. 14. Effect of varying working distance, within practical operating limits, in nonvacuum electron beam welding of ¼-in.-thick aluminum alloy 2219

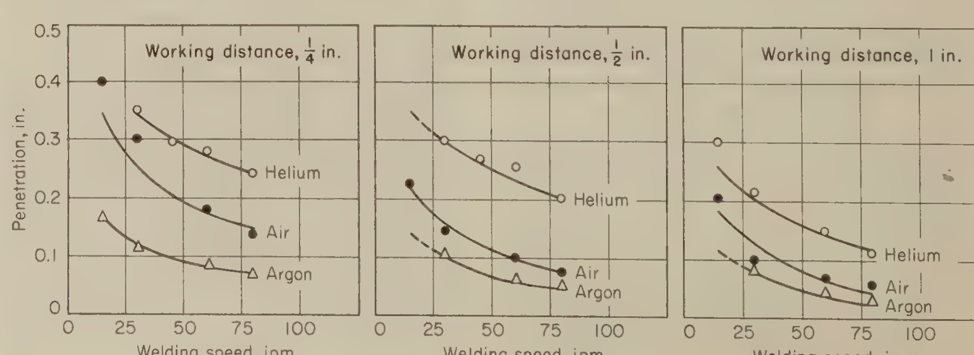
Welds having penetration greater than 1 in. have been obtained, but this ordinarily entails a substantial reduction in welding speed, accompanied by a corresponding increase in welding cost.

Figure 12 shows effect of welding speed on penetration of nonvacuum welds made on steel in air, using 12 and 25-kw beam power at ¼-in. distance. Figure 13 shows effect of welding speed on penetration of nonvacuum welds made on steel and aluminum in helium shielding.

The effect on penetration of varying working distance, within practical operating limits, is shown schematically in Fig. 14 for ¼-in.-thick aluminum alloy 2219. When the maximum working distance was used, penetration was only about 80%, and maximum weld width was about one-third greater than when the minimum working distance was used.

When a shielding gas is substituted for air in nonvacuum welding, assuming the same operating conditions, penetration will be greater when a gas is used that has a lower molecular weight (or nominal density) than that of air, and will be less when a gas is used that has a higher molecular weight than that of air. In tests on welding 4340 steel, using a fixed beam power of 6.4 kw, working distances of ¼, ½ and 1 in., and welding speeds of about 15 to 80 in. per minute, penetration was increased when helium was substituted for air and was decreased when argon was substituted for air, as shown in Fig. 15. The relative capacities of helium, air and argon to scatter the electrons of the beam by collisions of electrons with gas molecules are indicated by their molecular weights and relative densities, which are given below Fig. 15. On the average, when helium was used as a shielding gas, penetration depth was about twice that obtained when welding was done in air, and, when argon was used, about half that when welding was done in air. Thus, with helium shielding, penetration averaged about four times that with argon, especially at higher welding speeds. The speed at which a given thickness of 4340 steel could be welded with full penetration, using helium, was two to four times that with air, and using argon, 25 to 50% that with air.

Studies made of nonvacuum welding of steel pipe showed that, at speeds of 100 to 1000 in. per minute, full-penetration welds could be made in metal twice as thick if helium shielding gas was used instead of air. Table 2 gives the results of this comparison in terms of welding speed for joining steel pipe



Molecular weights: Helium, 4; air, 29; argon, 40
Relative densities: Helium, 0.14; air, 1.00; argon, 1.38

Fig. 15. Effect of shielding gas, working distance and welding speed on penetration for nonvacuum electron beam welding of 4340 steel, using a beam power of 6.4 kw

0.050 to 0.150 in. thick in air or in helium. Welding speeds were 2.16 to 2.24 times as great in helium as in air. Beam power used was 12 kw.

Weld Shape and Heat Input. Nonvacuum electron beam welds are generally wider and more tapered than high-vacuum welds (medium-vacuum welds differ only slightly in shape from high-vacuum welds — see Fig. 10).

Typical shapes of full-penetration welds made in 0.224-in.-thick aluminum alloy 2219 by nonvacuum and high-vacuum electron beam welding, and by gas tungsten-arc welding, are shown in Fig. 16, and conditions are given in the accompanying table.

Comparing the nonvacuum and high-vacuum electron beam welds in Fig. 16(a), heat input for the nonvacuum weld was about 40% greater, producing a midpoint weld width about 33% greater and a maximum crown width 160% greater than those of the high-vacuum weld. Comparing the nonvacuum electron beam weld to the gas tungsten-arc weld in Fig. 16(b), heat input for the typical nonvacuum weld was 32% of that for the arc weld, producing a midpoint weld width about 25%, and a maximum weld width about 56%, of the corresponding widths for the arc weld. Compared to the arc weld, the widest weld produced by nonvacuum electron beam welding under workable operating conditions was about 42% as wide at midpoint and about 70% as wide at the crown.

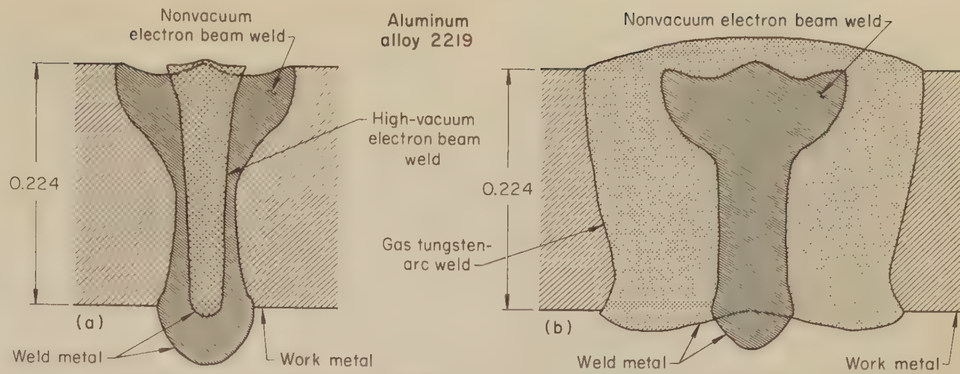
Weld shrinkage across nonvacuum electron beam welds is generally less than half that of gas tungsten-arc welds on the same work metal and thickness, and is typically about twice that for high-vacuum electron beam welds.

Studies on welding ¼-in.-thick aluminum alloy 2219 showed average shrinkage of 0.003 to 0.005 in. for high-vacuum welds, and 0.014 in. for high-heat-input nonvacuum welds, compared with a normal shrinkage of 0.030 in. for gas tungsten-arc welds.

Tooling. The basic welding unit consists of a power supply, an electron gun (emitter and beam transfer column), and controls like those used in a variety of welding applications. Tooling is generally designed specifically for welding a particular assembly in mass production. Providing fixtures and equipment that will permit welding at high speeds and will permit efficient work handling is the key to obtaining high production rates and low cost.

The work-handling equipment is at atmospheric pressure, instead of in a vacuum; hence general-purpose welding positioners and related fixtures are usually satisfactory. Hold-down clamping devices can be simpler than those often needed for arc welding similar parts, because angular distortion, or dihedral warpage, is generally low. Locating and alignment mechanisms are simpler than for welding in a vacuum, because of their accessibility and because beams are wider and such high accuracy is not required in tracking the joint. Maintenance of work-handling equipment is greatly simplified by its out-of-chamber location.

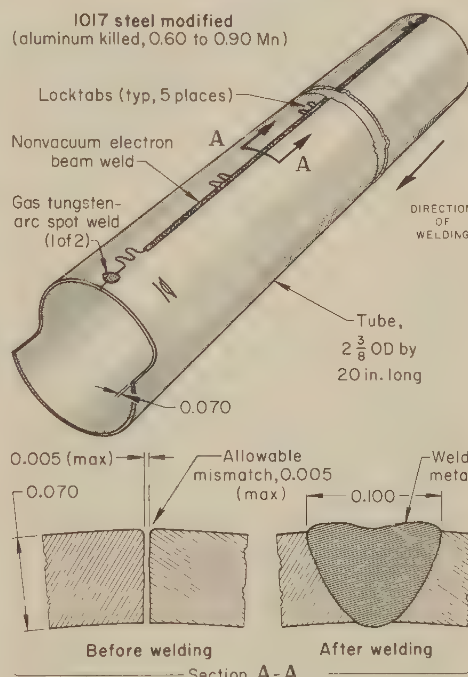
Production Applications. Nonvacuum electron beam welding has been used



Welding conditions	Fig. 16(a) High-vacuum EBW	Fig. 16(a) Nonvacuum EBW	Fig. 16(b) GTAW	Fig. 16(b) Nonvacuum EBW
Voltage, kv	150	140	13 (v)	140
Current, ma	20	30	270 (amp)	20
Welding speed, ipm	100	100	20	50
Welding energy, kj per inch	1.8	2.5	10.5	3.36

EBW = electron beam welding; GTAW = gas tungsten-arc welding.

Fig. 16. Comparison of full-penetration welds in 0.224-in.-thick aluminum alloy 2219, made by (a) *nonvacuum electron beam welding vs high-vacuum electron beam welding, and* (b) *gas tungsten-arc welding vs nonvacuum electron beam welding*



Conditions for Nonvacuum Electron Beam Welding

Joint type	Butt
Weld type	Square groove
Machine capacity	175 kv at 70 ma
Gun type	Self-focusing triode; fixed; with tungsten filament
Exit orifice	0.060 in. in diameter
Automation	Complete, except for manual loading and unloading
Working distance	0.20 in.
Welding power	175 kv at 45 ma
Operating vacuum:	
Upper chamber	10^{-4} torr
Lower chamber	3×10^{-1} torr (300 microns)
Workpiece environment	Ambient air (no shielding gas), at atmospheric pressure
Welding speed	250 ipm (typ)
Number of passes	One
Preheat and postheat	None
Production rate	20,000 pieces per day(a)
Annual production	5,000,000 pieces

(a) Production rate is based on using three welding machines for two shifts per day.

Fig. 17. Collapsible steering-column jacket that was joined by automatic nonvacuum electron beam welding in high-speed mass production, without the use of shielding gas (Example 467)

in commercial production of gears, wheels, ball joints, other automotive parts, refrigeration and appliance components, and tubing and pipe in continuous lengths. The two examples that follow describe the nonvacuum welding of carbon steel assemblies.

Example 467. Development of a Procedure for Nonvacuum Welding of Low-Carbon Steel in Automated Mass Production (Fig. 17)

The original design for the outer jacket of an automobile collapsible steering column called for 15 separate punching operations to be performed on 2⅜-in.-OD by 0.070-in.-wall steel tubing. This procedure, which involved no welding, was slow and costly, and could not meet the anticipated demand for an annual production of 5 million assemblies.

To increase the production rate and minimize costs, the part was redesigned for progressive piercing, blanking and forming from sheet, in a single press, and for welding of the longitudinal seam. At first, welding appeared to be the major obstacle in achieving cost and production objectives. Several joining methods were tried and compared before a satisfactory procedure was developed, based on nonvacuum electron beam welding.

Figure 17 shows part of a 20-in.-long section of the outer jacket partially welded to illustrate joint fit-up details. Blanks were sheared without waste from a 20-in.-wide coil, so that five pairs of locktabs mated exactly when the cylinder was formed. A tight longitudinal butt joint was made by interlocking and pinching the locktabs. A single gas tungsten-arc spot weld at each end of the workpiece was used to help maintain joint alignment during handling and storage. A maximum tolerance of 0.005 in. was allowed in the joint opening.

Weld Requirements. The weld had to be able to withstand the following service. Thirty-two hardened steel balls were uniformly distributed between the outer jacket and an inner steel tube by means of a plastic sleeve that served as a spacer. The tubes were then sized so that the balls slightly indented the tube walls. Thus, when the tubes were forced to telescope from the impact of a collision, the balls, which were fitted tightly between the two tubes, would retard the telescoping action.

Because tube concentricity was essential to the stability of the retarding force, warpage had to be avoided in welding the outer jacket. In addition, it was desirable to minimize weld reinforcement because of the sizing operation. Other weld character-

istics were subordinate to acceptance criteria based on these three requirements. The sizing operation provided an incidental check on joint strength.

Process Selection. When mechanical clamping and gas tungsten-arc spot welding proved inadequate, continuous gas tungsten-arc welding was tried. Samples developed adequate strength, but the warpage of approximately 0.050 in. per foot was too great. Plasma-arc welding produced similar results. Electron beam welding in a vacuum chamber satisfied all mechanical requirements, warpage being held to approximately 0.005 in. per foot. However, the relatively high vacuum required long pumpdown times, slowing production.

Nonvacuum electron beam welding satisfied all requirements. Weld strength was adequate to meet the collapsing forces; warpage was held to a tolerable level of about 0.008 in. per foot; excessive weld reinforcement was avoided; welding speeds of 200 to 300 in. per minute were attained without the need for welding in a vacuum.

Equipment Features. The generating and focusing equipment of the nonvacuum electron beam welding machine consisted of an upper and lower chamber. A high vacuum was maintained in the upper chamber, where the generating gun was located. Magnetic focusing coils were located in the lower chamber, where a medium vacuum was maintained.

The electron beam passed from the gun, through a small aperture in the upper chamber, through the focusing coils, and exited from the lower chamber through a 0.060-in.-diam orifice in a water-cooled copper orifice plate. The workpiece, positioned in ambient air, was held approximately 0.20 in. from the exit orifice, to minimize energy loss by scattering. No shielding gas was used.

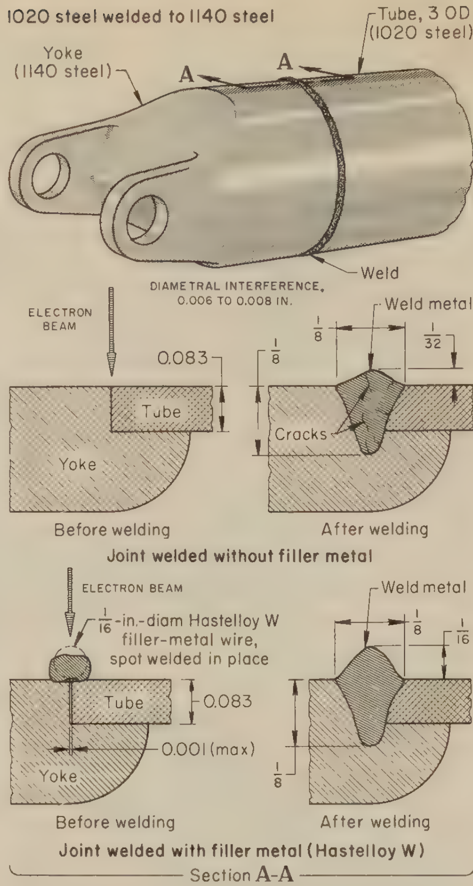
The small diameters of the exit orifice and of the aperture between chambers served to hold the quantity of air entering the lower and upper chambers to a level within the capacity of the vacuum pumps. Filament life varied from 15 to 20 hr.

Material Selection. To suit the various requirements of piercing, shearing, forming, welding and indenting, a low-carbon steel was selected. The material, which was purchased as coiled sheet, was an aluminum-killed 1017 steel with modified manganese content (0.60 to 0.90%). This steel was similar to aluminum-killed 1018, but it was less expensive because of a break in the steel price structure.

Despite the fact that the steel was aluminum killed, considerable outgassing occurred during welding, indicating that a rimmed steel might have caused problems in welding. Variations between different heats of the same steel were noted in welding; some heats produced acceptable welds with joint openings as wide as 0.010 in.; others required a smaller joint opening. For this reason, 0.005 in. was established as the fit-up tolerance.

Preweld Cleaning. Alkaline cleaning removed the oil film used for protection in shipping from the steel mill and for wrap forming. It was found that the oil had little or no effect in welding and on weld strength in collapsing tests. However, the oil caused smoke and soot that contaminated fixtures and equipment.

Welding Conditions. Because the operation was automated for high-speed production, accurate control of positioning, travel and weld timing was necessary. The welding conditions used in the procedure are summarized in the table with Fig. 17. Because neither beam oscillation, nor upslope-downslope current modes, nor starting nor runoff tabs were used, beam initiation and termination were critical. The beam had to be initiated at the exact desired starting point of the weld joint. If the beam was initiated before the moving workpiece reached the beam position, a hole would result. Similarly, the beam had to be terminated approximately ⅜ in. from the intended end of the weld seam, to avoid a hole at the end of the workpiece.



Joint type	Circumferential butt; rabbeted, self-backing
Weld type	Square groove
Machine capacity	175 kv at 40 ma
Workpiece environment	Helium shielding gas, at atmospheric pressure
Filler metal	1/16-in.-diam Hastelloy W(a)
Working distance	1¼ in.
Welding power	175 kv at 35 ma
Beam focal point	At work surface
Beam spot size	0.010-in. diameter
Beam deflection	None
Welding speed	94 ipm
Number of passes	One
Welding time	6 sec
Preheat and postheat	None
Fixtures	Turning rolls

(a) Preplaced by resistance spot welding

Fig. 18. Joint between tube and coupling yoke of a drive shaft that was welded using nonvacuum electron beam welding and helium shielding gas. The yoke was made of resulfurized steel, which caused weld cracking until a suitable filler metal was added. (Example 468)

A jet of compressed air was directed across the exit orifice of the lower chamber to blow the metal vapors and other toxic fumes into an exhaust duct. Ozone, which was formed when the electron beam struck the atmosphere, also had to be removed by forced ventilation. The action of the air jet also served to: (*a*) keep the exit orifice and the orifice plate from being fouled, (*b*) prevent fumes from entering the lower chamber, and (*c*) create a venturi action across the exit orifice to help maintain the vacuum. The compressed air had to be dry because moisture carried in the air would reduce welding efficiency if it entered the lower chamber.

Automation. Three automated welding setups were built, each consisting basically of a circular table that rotated past a fixed electron beam machine. One welding operator loaded and unloaded each table, and a fourth operator monitored and serviced the three welding machines.

Each table contained eleven fixture stations. Parts were manually loaded into a fixture that positioned the joint for welding. As each fixture reached the welding station, a limit switch was tripped, initiating the automatic welding cycle. At this point, the fixture was cam guided to travel in a straight line for the precise length of the weld. Upon returning to the operator station, the part was manually unloaded. Table rotational speed was approximately 1 rpm, or about 650 parts per hour. With crews operating three machines on two shifts, production averaged 20,000 parts per day, and yearly production was approximately 5 million parts.

X-Ray Shielding. Lead shielding was required for protection of personnel. This was done by placing a ¼-in.-thick lead shield tunnel over two-thirds of the circular table and the machine, leaving the operator one-third of the table for loading and unloading. Because considerable electron scattering occurred, lead baffles were used to block off stray radiation.

Quality Control. So long as the entire system — from material procurement to welding — was kept within specifications, adequate welds were produced. As observed earlier, the sizing operation served as a check on weld strength; it also served as a check on warpage and excessive flash, since the operation could not proceed if these factors were out of tolerance. All parts were visually inspected for weld cracks and correct location of the weld on the joint. Twice each shift, parts were checked for dimensional variations.

Ordinarily filler metal is not used in nonvacuum electron beam welding. The addition of a suitable filler metal may be helpful, however, in joining metallurgically incompatible metals or in avoiding weld cracking caused by hot shortness. Selection of the filler-metal composition in such applications is critical, as in the following example, in which a filler metal was used to avoid cracking in welding a medium-carbon resulfurized steel to a low-carbon steel. This welding operation also was unusual in being done at a working distance of 1¼ in., instead of the customary working distance of less than ¾ in.

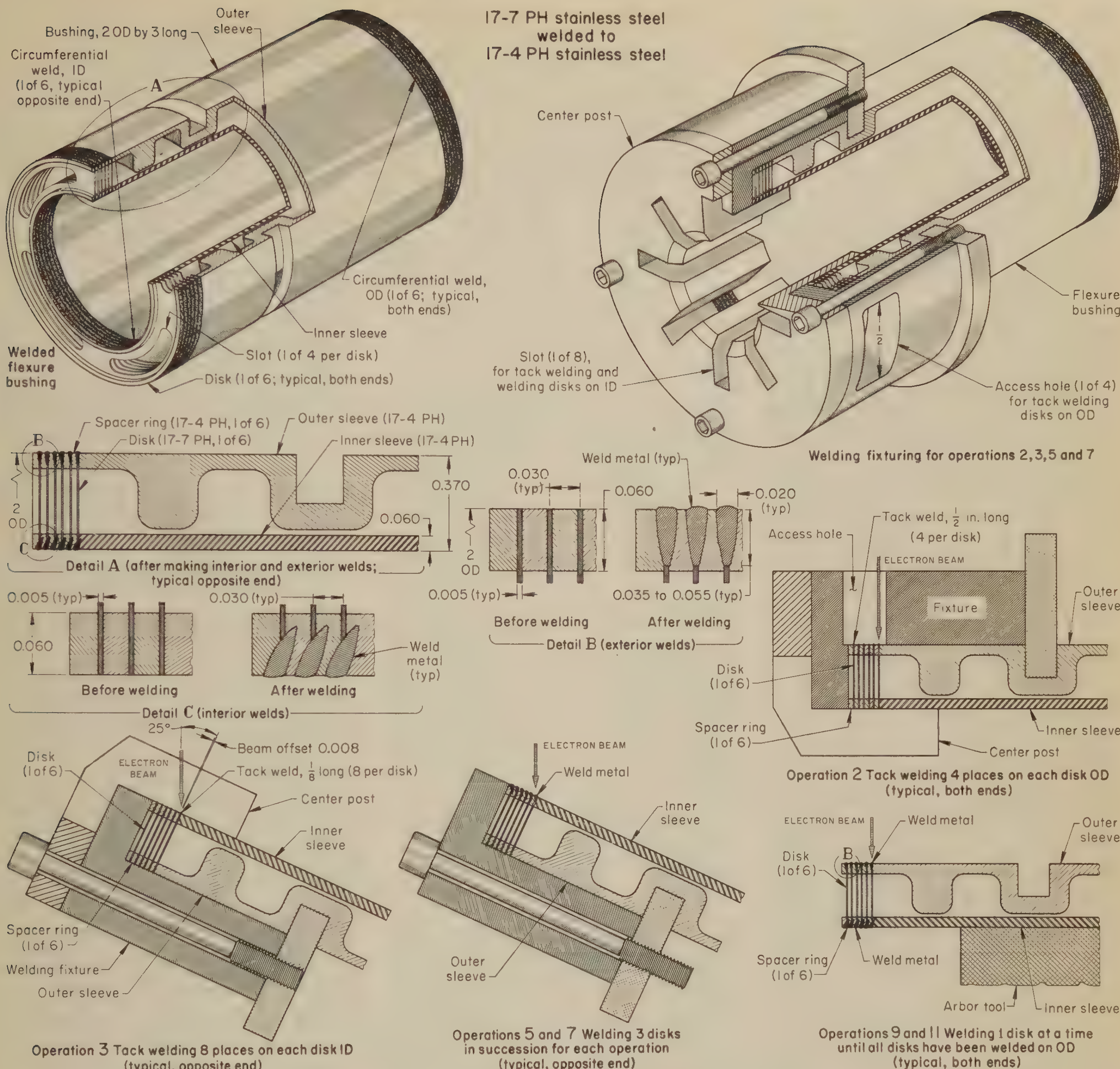
Example 468. Use of Filler Metal To Avoid Cracking in Nonvacuum Welding of 1140 Steel to 1020 Steel (Fig. 18)

Drive shafts were made in small quantities by electron beam welding 1020 steel tubing to 1140 coupling yokes. The nonvacuum method and helium shielding gas were used. The joint of a typical 3-in.-diam drive shaft is shown in Fig. 18. Joints of this type were required to match the ultimate shear strength of the 1020 tube, and to provide a fatigue life of 100,000 cycles or better at 50% of the elastic limit.

Initially, the weld between the low-carbon steel tube and the resulfurized carbon steel yoke was attempted by fusing the joint in a single pass. This was done by rotating the shaft under the beam exit orifice of the machine, using a helium atmosphere. Although high welding speeds were used, many large and small cracks (Fig. 18) developed in the weld, induced by the 0.08 to 0.13% sulfur content of the 1140 steel.

To prevent cracking, various filler metals were tried. Preheating and postheating were not considered because the benefits were doubtful and the cost of additional labor was unwanted. The filler metal that was found to be most successful was a 1/16-in.-diam wire of Hastelloy W. (This alloy, having a nominal composition of 62 Ni, 24.5 Mo, 5 Cr and 5.5 Fe, is useful in welding dissimilar metals.) Before welding, the filler metal was resistance spot welded in place over the joint, as shown in Fig. 18.

Welding was done using the conditions given in the table with Fig. 18. The weld was completed in one revolution of the work, for a welding time of 6 sec. Working distance was 1¼ in.



Item	Tack weld OD	Tack weld ID	Full weld ID	Full weld OD
Weld length	½ in. long (four)	⅛ in. long (eight)	Continuous	Continuous
Welding power	120 kv at 2 ma	120 kv at 2 ma	120 kv at 6 ma	120 kv at 3.2 ma
Working distance	6 in.	6 in.	6 in.	6 in.
Beam focal point	Sharp on surface	Sharp on surface	Sharp on surface	Sharp on surface
Welding speed	About 60 ipm (8 rpm)	About 60 ipm (10 rpm)	About 60 ipm (10 rpm)	About 60 ipm (8 rpm)
Beam direction	Normal to surface	25° off normal to surface	25° off normal to surface	Normal to surface
Number of passes	One	One	One, plus 30° downslope	One, plus 30° downslope

Machine characteristics were as follows: power rating, 150 kv at 25 ma; gun type, fixed, hairpin tungsten filament; vacuum-chamber size, 23 by 36 by 36 in.; maximum vacuum, 10^{-6} torr; fixtures, assembly and tack welding tool, rotatable and inclinable chuck. Cosmetic passes, when used, were made with a welding power of 110 kv at 2 ma, with a defocused beam at 60 ipm, and with circular oscillation at 60 hertz. Pumpdown time for each operation was 5 min. Beam oscillation was 0.015-in. diameter, circular, 500 hertz.

Fig. 19. Flexure bushing (upper left) that involved precision welding of six thin, annular disks at each end to maintain concentricity between inner and outer sleeves while permitting relative displacement in the axial direction. Fixture tool maintained alignment of six disks and twelve ring segments for automatic tack welding. (Example 469)

Welding of Complex Assemblies

The high degree of dimensional control obtainable in the electron beam welding process sometimes makes it possible to weld complex assemblies that would be unweldable by other processes. To make effective use of the precision capabilities of the beam, however, the workpiece dimensions, and the tooling and guidance devices used, must equal one another in precision.

The lengthy and complicated procedure used in fabricating a complex precision assembly for a lunar-module engine required elaborate fixturing for making many closely spaced, partial-penetration welds, using low heat

input, as described in the following example. Examples 489 and 496 also describe electron beam welding of complex portions of the same engine.

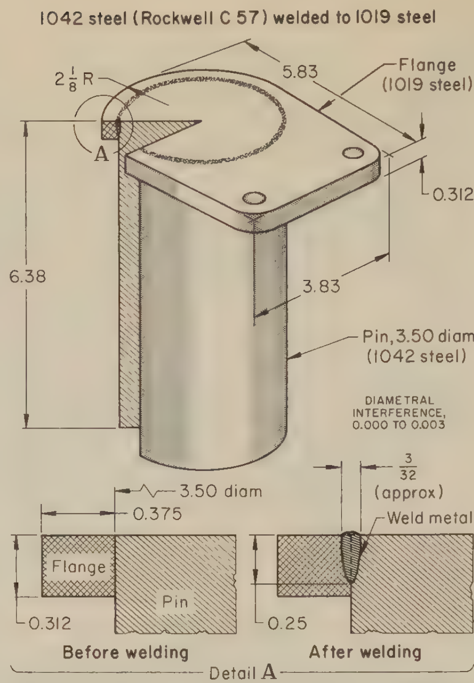
Example 469. Making 144 Tack Welds and 24 Partial-Penetration Welds at Thin, Closely Spaced Joints of a Complex Precision Assembly (Fig. 19)

The capability of electron beam welding to discriminate between closely spaced joints requiring partial penetration in thin material was fully exploited in fabricating the precipitation-hardening stainless steel flexure bushing shown in Fig. 19. The bushing was used in a lunar-module landing engine, to maintain concentric flow of fuel and oxidizer at the point of combustion. The bushing, which consisted of two concentric sleeves of 17-4 PH stainless steel, was designed to permit relative displacement in the axial direction without changing concentricity. This was accomplished by fitting and welding twelve annular spacer rings and six annular flexure disks to each end of the bushing, as shown in detail A of Fig. 19. The spacer rings were made of 17-4 PH and the flexure disks of 17-7 PH stainless steel.

To promote disk flexibility, the 0.005-in.-thick flexure disks were slotted by chemical machining, as shown in the over-all view at the top left in Fig. 19. To maintain optimum flexibility after welding, only partial penetration of the 0.060-in.-thick spacer rings could be permitted; full penetration would have damaged the disks or impaired the flexing action. The most effective means of controlling penetration was by use of the beam-oscillation technique at low amperage and fast travel speed.

Enlarged views of the sleeves, spacer rings, and disks are shown in detail A of Fig. 19; the exterior welds, in detail B; and the interior welds, in detail C. Enlarged views of operations 2, 3, 5, 7, 9 and 11 (see Sequence of Operations list in column 3) are shown in Fig. 19.

A precision fixturing tool was made to ensure correct alignment of the rings and disks on assembly and to provide for automatic tack welding. The tool consisted of an outer casing with a removable center post to contain and line up the components, a collar, and an end washer to hold the assembly together. Figure 19 (top right) shows a cutaway perspective view of this fixture, with the parts assembled for tack welding. Four openings in the outer casing and eight slots in the center post were cut to admit the electron beam for tack welding as the assembly rotated. Between tack welds, beam energy was absorbed by the tool body, the beam being out of focus at these points.



Joint type	Circular corner
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald; fixed
Vacuum-chamber size	36 by 36 by 36 in.
Maximum vacuum	About 10^{-6} torr
Fixtures	Eight-workpiece rotating tool; table with x-y motion control
Welding power	130 kv at 25 ma
Welding vacuum	10^{-3} to 10^{-4} torr
Pumpdown time	5 min
Working distance	5.4 in.
Beam focal point	0.50 in. below work surface
Beam oscillation	None
Preheat and postheat	None
Number of passes	One, plus ½-in. downslope
Welding speed	39 ipm
Production rate	25 pieces per hour

Fig. 20. Flanged pin made by electron beam welding a flange and a hardened pin, for lower material consumption and simpler processing than in previous method of production, machining a one-piece forging and hardening it (Example 470)

The circumferential weld on the outside was made with the electron beam vertical and normal to the surface (12 o'clock), the bushing being rotated about its horizontal axis. The welds on the inside were made with the axis of the bushing tilted up 25° from the horizontal, so that the vertical beam could just reach the innermost disk without interference. Details A and C in Fig. 19 show the oblique penetration of the inside welds, although the actual welding was done at 6 o'clock with the beam pointed vertically down and offset, as shown in Fig. 19 (operations 3, 5 and 7). (For simplicity, the parts in details A, B and C are shown positioned for the outside welds.) Offsetting the beam approximately 0.008 in. from the joint for the oblique inside welds produced the best weld profile.

The electron beam welding procedure, as outlined below, was lengthy, including at least 20 vacuum pumpdowns and requiring great care in making the 144 tack welds and 24 circumferential welds.

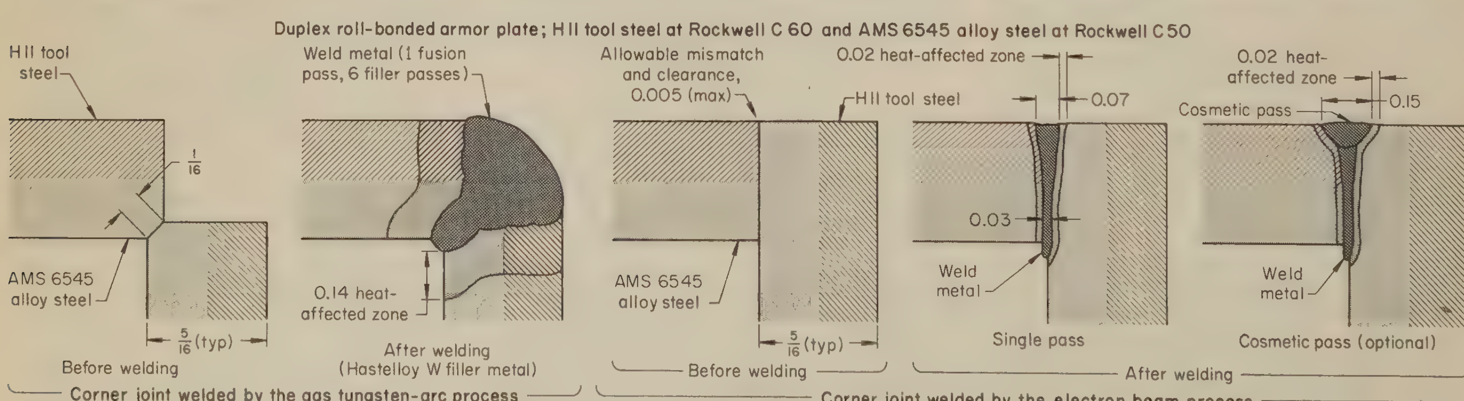
Sequence of Operations (See Fig. 19)

1 Assemble rings and disks to one end of bushing by means of fixture.
2 Tack weld each disk on outside diameter (four places).
3 Tack weld each disk on inside diameter (eight places).
4 Vent machine; remove clamp washer and slotted center post; cool part with liquid propellant; install new clamp washer.
5 Weld three rings in succession on inside diameter.
6 Vent machine; cool part with liquid propellant; tighten clamp washer.
7 Weld remaining three rings on inside diameter.
8 Repeat operations 1 through 7 for opposite end.
9 Remove fixture; mount assembly on arbor tool; weld outside of one ring at each end.
10 Vent chamber; cool part; tighten tool.
11 Continue welding, as in operations 9 and 10, until all six rings on each end are welded.
12 Use cosmetic passes after operations 7 and 11, if necessary, to obtain a smooth weld without undercut.

Several design features of the complex fixture were especially suited to vacuum service. There were no ball bearings or sliding contact surfaces that needed lubrication. The unit was unaffected by moderate contamination from hot gases or metal vapors and could operate in a vacuum as well as in an air atmosphere.

All fixturing was applied, and adjustments to fixtures were made, in a laboratory equipped for the purpose. Operating data and machine characteristics are given in detail in the table that accompanies Fig. 19. After the welding described above was completed, a thick, annular disk (not shown) was temporarily welded to each end of the bushing, to prevent flexing and damage during postweld finish machining. After machining, these disks were removed.

Although fabrication by electron beam welding was exacting and lengthy, the procedure solved a complex and potentially more difficult manufacturing problem.



Joint type	Corner
Weld type	Square groove
Machine capacity	30 kv at 500 ma
Vacuum-chamber size	112 by 50 by 62 in.
Maximum vacuum	10^{-7} torr
Fixtures	Assembly jig; travel carriage
Welding power:	
Penetration pass	30 kv at 170 ma
Cosmetic pass	19 kv at 95 ma
Welding vacuum	10^{-5} torr
Pumpdown time	10 min
Beam focal point, penetration pass:	At surface
Beam oscillation	None
Welding position	Flat
Welding speed:	
Penetration pass	60 ipm
Cosmetic pass	32 ipm
Preheat and postheat	None

Fig. 21. Cross sections through corner joints and welds made in duplex roll-bonded armor plate, showing approximate differences in sizes of the welds and the heat-affected zones resulting from electron beam welding and gas tungsten-arc welding (Example 471)

Welding of Hardened and Work-Strengthened Metals

The full properties of hardened and work-strengthened base metals can be retained on functional surfaces very close to the narrow electron beam weld zone. This aspect of electron beam welding can often simplify difficult and costly manufacturing procedures, as in the example that follows.

Example 470. Welding a Hardened 1042 Steel Pin to a Flange (Fig. 20)

A flanged pin (see Fig. 20) originally was machined from a single forging of 1042 steel and then was heat treated. Machining time was considered to be excessive, and the amount of metal removed was substantial. To meet the final hardness requirement of Rockwell C 57, which was required only for the cylindrical surface of the pin, the entire part was hardened in a difficult heat treatment operation. To simplify the manufacturing procedure, the part was redesigned as a two-piece weldment.

The weldment consisted of a pin cut from 1042 round stock and a flange machined from 1019 plate, thus reducing material costs. Electron beam welding was selected to join the two parts because, with this process, the pin could be welded in the hardened condition, without softening on the critical area. The dimensional tolerances on the flange could be maintained easily, and postweld heat treatment of the pin only was a simple, trouble-free operation. The weld was a single-pass, partial-penetration, square-groove weld between the flange and the pin (Fig. 20).

To reduce the unit cost occasioned by the pumpdown time required by the high-vacuum electron beam welding machine that was available, and to increase the production rate, eight workpieces were loaded in the chamber at the same time and were welded in sequence. A commercially available fixture, modified to suit the application, was used. The fixture consisted of an aluminum box that could be bolted to the table of the vacuum-chamber positioner, which was equipped with an operator-controlled x-y drive. The top of the fixture was fitted with eight tubular receptacles into which the pin assemblies were inserted. The ends of the pins were engaged by a collet attached to a gear. Each of the pins was simultaneously rotated about its own axis by a chain belt that engaged the eight gears.

Before welding, the components were machined for an interference fit, vapor degreased, press fitted, and assembled into the fixture, and the fixture was bolted in place. During vacuum pumpdown, the beam was optically aligned on the joint of the first workpiece as the pieces were rotated at full welding speed (3.54 rpm). Two tack welds were made at approximately 120° intervals by manually energizing the beam intermittently. At 360°, full welding power was initiated and continued for one revolution, with current tapering to zero over an additional ½-in. overlap. The positioner was then moved to the next piece, and the operation was repeated until all eight assemblies were welded.

Welding conditions are summarized in the table with Fig. 20.

In the example that follows, electron beam welding was chosen over gas tungsten-arc welding because of the narrow fusion and heat-affected zones obtained by the electron beam process.

Example 471. Selection of Electron Beam Welding To Minimize Tempering in the Heat-Affected Zone in Joining Hardened Duplex Armor Plate (Fig. 21)

Fabrication of armor for military aircraft involved the welding of corner joints in 5/16-in.-thick armor plate. The armor plate was made by roll-bonding H11 tool steel to an alloy steel (AMS 6545) containing 9% nickel, 4% cobalt and 0.30% carbon. Welding was done with the plate in the hardened condition, the H11 steel being at Rockwell C 60 and the alloy steel at Rockwell C 50. The plate was not difficult to weld. Either gas tungsten-arc or electron beam welding could be used to obtain sound welds using the joint designs shown in Fig. 21.

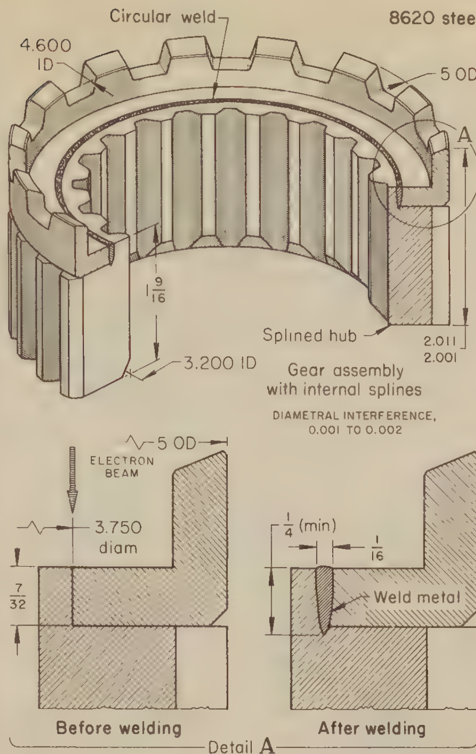
The weld and heat-affected zone of the electron beam process are compared with those of the gas tungsten-arc process in Fig. 21. Joint designs differed; if the joint for gas tungsten-arc welding had been made the same as the joint for electron beam welding, a V-groove would have been required, and about the same amount of weld metal would have been needed. Gas tungsten-arc welding was done in one fusion pass and six filler-metal passes, using 0.062-in.-diam Hastelloy W wire.

Electron beam welding was done in a single pass, using the equipment and the welding conditions given in the table with Fig. 21. Because of occasional undercutting, a second (cosmetic) pass was sometimes used. Even when the second pass was used, the weld and the heat-affected zone were much narrower than were those from arc welding, and they were unaffected below the crown of the weld. Because the general effect of the welding heat was to decrease the hardness and strength of the base metal, electron beam welding, which produced less heat, was selected.

There were no unusual problems associated with the electron beam welding procedure. Plates were machined square and then were degreased. Just before welding, surface films were removed from all surfaces to be welded, by brushing with a stainless steel wire brush followed by wiping with alcohol. The plates were then fixtured into an assembly roughly resembling a bathtub having sides about 10 in. high and a floor area of about 20 by 40 in. A maximum tolerance of 0.005 in. was allowed on fit-up for joint mismatch and clearance. Starting and runoff tabs, made of the same duplex plate, were attached to joint ends to contain variations in beam initiation and termination. The fixture was a simple arrangement of toggle clamps and stainless steel blocks that could be set up for flat-position welding on a track-guided carriage in the vacuum chamber.

After beam alignment and vacuum pumpdown, each joint was welded in a single pass without tack welding and without beam oscillation. Because undercutting occurred where fit-up approached the maximum tolerance, a second (cosmetic) pass occasionally was used. The effect of the cosmetic pass on the weld cross section is shown in Fig. 21; the machine settings for the defocused beam used to make the cosmetic pass are in the table with Fig. 21.

The capability of electron beam welding to produce deep, narrow welds makes it possible to design steel assemblies that include splines and bearing or wear surfaces very close to the welded joint, as in the next example.



Joint type	Circular butt; self-backing
Weld type	Square groove
Machine capacity	30 kv at 50 ma
Gun type	Fixed
Vacuum-chamber size	50 by 30 by 42 in.
Maximum vacuum	10^{-4} torr
Filler metal	None
Fixtures	Chuck; turntable
Welding power	30 kv at 22 ma
Welding vacuum	0.1 torr
Pumpdown time	0.25 min
Working distance	8 in.
Beam focal point	1 in. above work surface
Welding speed	30 ipm
Number of passes	One, plus 20° overlap

Fig. 22. Transmission-gear assembly designed for compact, two-piece fabrication by electron beam welding. Other welding processes could not provide satisfactory depth-to-width ratios, nor freedom from distortion or melt-through of nearby splined surfaces. (Example 472)

Example 472. Medium-Vacuum Welding of a Transmission-Gear Assembly, With Splines Close to the Joint (Fig. 22)

Double gears of the type shown in Fig. 22 were designed as two-piece weldments to reduce weight and save space in a transmission system. The gear assembly consisted of two components machined from normalized 8620 steel and assembled with an interference fit of 0.001 to 0.002 in. on the 3.750-in.-diam, 7/32-in.-deep joint, as shown in detail A in Fig. 22. This joint required a ¼-in.-deep weld, to ensure complete joint penetration.

Several welding processes were considered for making small quantities of a number of different gears of this type. There were a number of restrictive requirements for the weld; the most important involved the depth-to-width ratio. The proximity of the internal spline surfaces to the weld joint (slightly over ⅛ in.) made it necessary that the depth-to-width ratio be greater than 2 to 1, to avoid overheating the spline.

On the basis of this restriction, the weight-saving, compact design shown in Fig. 22 could be used only if welding were done by the electron beam process. There was no problem in obtaining a 4-to-1 depth-to-width ratio with electron beam welding. Carburizing followed welding.

The gear assemblies were welded in a single pass, using medium-vacuum equipment, with the conditions given in the table with Fig. 22. No distortion occurred. Although, because of the small quantity of parts involved, electron beam welding was the most costly process, it was the only one that could do the job.

In addition to confining the decrease in base-metal properties to a very narrow zone, as illustrated in the preceding three examples, electron beam welding of hardened or work-strengthened metals also generally produces joints superior in quality to those produced by arc welding.

Fourteen examples in this article deal with electron beam welding of hardened ferrous and nonferrous met-

als. The work metals involved and the example numbers are as follows:

Carbon steels 470
Alloy steels 465, 471, 472, 486, 504, 505
Tool steel 488
Stainless steel 489
Aluminum alloys 475, 493, 494
Copper alloy 502
Titanium alloy 496

Exceptions. Some high-strength steels cannot be electron beam welded in the hardened condition without cracking or an unacceptable decrease in strength and hardness. These steels are normalized or annealed before welding and heat treated for controlled strength and hardness after welding. This order of operations was followed in welding 4340 steel in Examples 464 and 503, and 52100 steel in Example 487.

Controlling Heat Effects

The extent of heat-affected base metal in electron beam welding is controlled mainly by regulating the width and shape of the weld. In general, the width of the heat-affected zone is proportional to the average width of the weld, which also strongly influences shrinkage and distortion.

Damage to heat-sensitive attachments, inserts or encapsulated materials close to the weld joint is controlled mainly by regulating the width and shape of the weld bead. Damage to nearby finished functional surfaces on the workpieces or to nearby drilled or tapped holes or other critical features of the workpieces can often be avoided in electron beam welding because of the narrowness of the welds, as in Examples 480, 481 and 496.

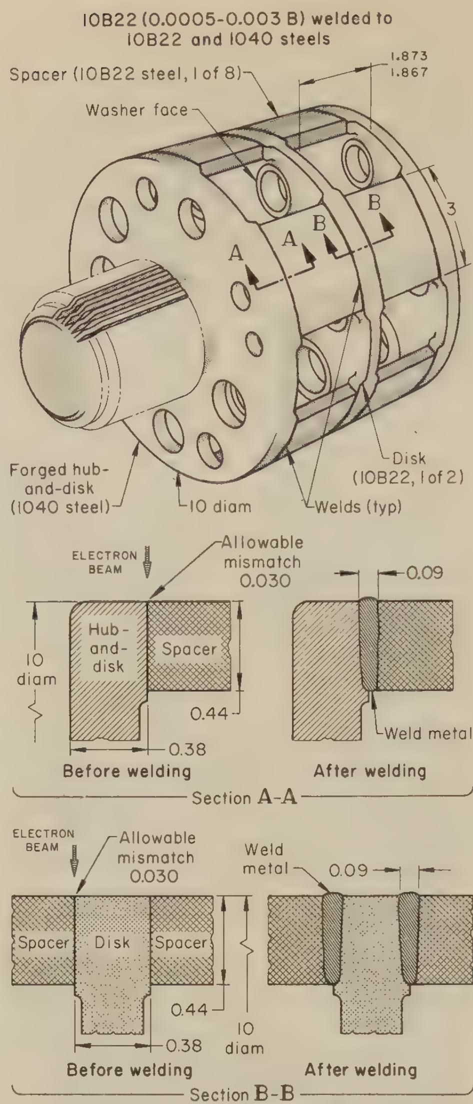
Joint designs that provide constricted sections near the weld to retard heat transfer from the weld, or that provide an integral heat sink, and the use of external heat sinks or chill bars are also helpful in controlling heat effects in electron beam welding (see Joint Design, page 521, and Welding of Thin Metal, page 536).

Holding shrinkage and distortion to low values was important in nearly all of the examples in this article. In the example that follows, narrow full-penetration welds with only a slight taper allowed final sizing of all components before assembly and welding.

Example 473. Electron Beam Welding To Maintain Dimensions of Prefinished Components for Minimum Shrinkage and Distortion (Fig. 23)

Planetary-gear carriers for tractor transmissions originally were machined from one-piece ductile iron castings. When the number of gears was increased from nine to twelve for greater power selectivity, the carriers were redesigned for electron beam welding (Fig. 23). The change from a casting to a weldment was made because: (*a*) the one-piece design precluded access for accurate machining of the larger number of washer faces, and (*b*) to meet higher strength requirements, the hardness of the casting would have had to be increased, which would have increased machining difficulties. Arc welding was ruled out because of excessive shrinkage and distortion.

Each weldment consisted of two disks, an integral hub-and-disk, and eight spacers. All parts were made of 10B22 (boron intensified) steel, except the hub-and-disk, which was forged in one piece from 1040 steel. Composition of the 10B22 steel was 0.19 to 0.25 carbon, 0.60 to 0.90 manganese, 0.04 max phosphorus, 0.05 max sulfur, 0.15 to 0.30 silicon, 0.0005 to 0.003 boron. Sixteen 3-in.-long complete-penetration welds were made to join the disks and spacers.



Joint types	Corner and T; circumferential (see illustration)
Weld type	Square groove
Machine capacity	150 kv at 40 ma (6 kw)
Vacuum-chamber size	36 by 36 by 36 in.
Maximum vacuum	About 10^{-6} torr
Fixtures	Clamping jig; lathe-type positioner
Preheat	None
Welding power	110 kv at 35 ma
Welding vacuum	10^{-4} torr
Working distance	8.75 in.
Beam focal point	At work surface
Beam oscillation	None
Welding speed	40 ipm (1.27 rpm)
Number of passes	One per joint
Production rate	Four assemblies per hour
Postheat	Induction harden splined hub to Rockwell C 50

Fig. 23. Planetary-gear carrier made to strength and accuracy requirements, for which electron beam welding permitted use of prefinished components, for minimum shrinkage and distortion (Example 473)

The new design and the use of electron beam welding made it possible to finish all components by conventional machining methods before welding. Electron beam welding was the only process by which the joints could be fully penetrated in a single pass with low heat input, to produce a narrow, only slightly tapered weld. Shrinkage and distortion were minimal.

Before welding, the two 10B22 disks and the 1040 hub-and-disk forging were in the hardness range of 241 to 285 Bhn, and the 10B22 spacers were in the hardness range of 207 to 241 Bhn. The only heat treatment after welding was selective induction hardening and tempering of the splined hub to Rockwell C 50.

The disks and the joint surfaces of the spacers were machined to a 32-micro-in. finish. They were vapor degreased, and then assembled and aligned in a holding fixture designed for mounting between the headstock and tailstock of a lathe-type positioner located within a vacuum chamber. The assembly rotated about a horizontal axis with the electron beam gun in a fixed vertical position. Beam alignment was done by telescope; welding was observed directly, through chamber windows. A second fixture was loaded while the first one was in the vacuum chamber. The tooling was also equipped with limit switches that turned the beam on and off for the interval required by each spacer. To avoid heat buildup, the two welds at the center disk were made first and last. Welding conditions are given in the table with Fig. 23.

Maximum weld width was about 0.090 in., for a depth-to-width ratio of 5 to 1.

Heat-Sensitive Attachments and Inserts. Narrow, closely controlled electron beam welds, with low heat input, can be made in close proximity to heat-sensitive attachments, inserts or encapsulated materials without damaging them, often when no other welding process can meet this requirement, as in the next two examples.

Example 474. Full-Penetration Welding of an Aluminum Alloy Section ⅛ In. Thick That Encased Nuclear Fuel Only 0.030 In. Away From the Joint (Fig. 24)

A nuclear fuel element consisting of a sheet of uranium-aluminum alloy that was clad with 99.9% aluminum on all sides and formed into a tube ¾ in. in outside diameter and 48 in. long, had a total wall thickness of about ⅛ in. The location of the longitudinal welded joint, relative to the cladding and the fuel, is shown in Fig. 24. Specifications for welding prohibited the fusion zone from extending to the fuel core material, which approached within 0.030 in. of the joint edge. Joint penetration had to be as deep as possible, without drop-through or the formation of an appreciable underbead. The outside weld face had to be smooth and flat.

An electron beam welding procedure, and the welding conditions shown in the table accompanying Fig. 24, were developed to meet the requirements. Details of the procedure were as follows:

A high-vacuum electron beam welding machine was used because it was the only type available. The welding could have been done more quickly in a medium-vacuum machine because pumpdown time would have been less. Gas tungsten-arc welding could have met the penetration requirements, but a wider fusion zone would have resulted, with the danger of melting through into the fuel.

Proper cleaning of the weld-joint surfaces was essential in obtaining porosity-free welds to meet radiographic standards. After edge preparation, the flat plates were vapor degreased, cleaned in a commercial cleaner, and rinsed in water. They were then formed into cylinders and vapor degreased in trichlorethylene.

Joint design was a tightly fitting butt joint with a tolerance of +0.010 in. max, as shown in Fig. 24 (lower left). This was obtained by machining the joint edges and clamping the cylinder in the split stainless steel fixture shown at the upper right of Fig. 24. No filler metal was used.

To protect the tube from weld spatter and to prevent possible impingement of the beam on the side of the tube opposite the weld, a thin aluminum spatter shield, also shown in Fig. 24, was loosely inserted.

The fixtured tube was mounted on a sliding carriage having a variable-speed

drive. Welds were initiated and terminated on starting and runoff tabs (not shown). The welding conditions given in the table with Fig. 24 were determined by welding test pieces.

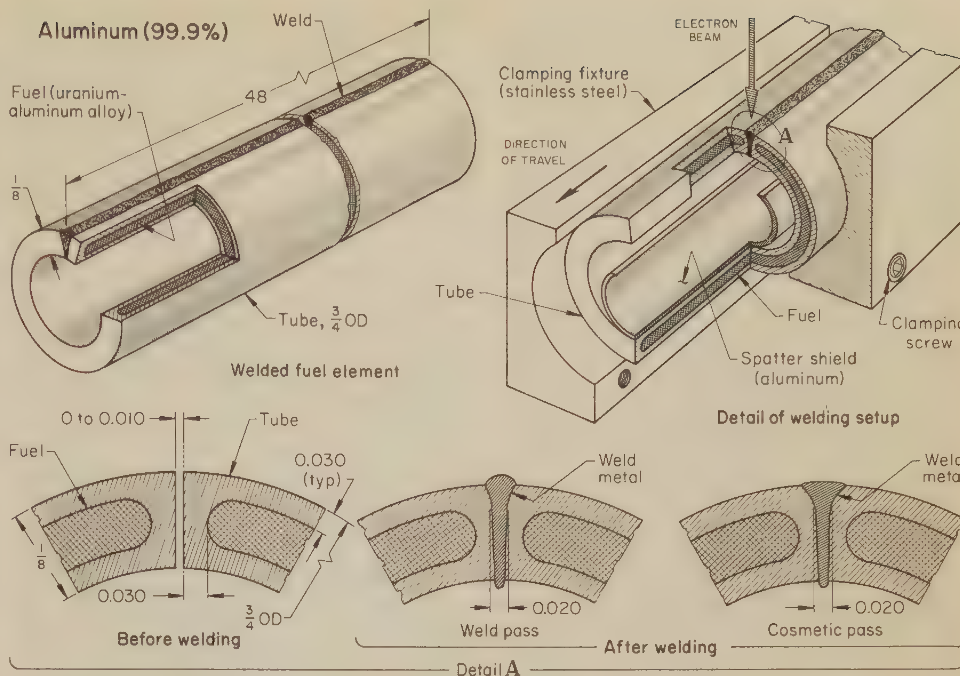
After pumpdown and beam alignment, the weld was made in a single pass, using a beam sharply focused on the workpiece surface. (Detail A in Fig. 24 shows the typical weld shape and dimensions.) Power and focus settings were then changed to form a beam of lower energy and larger spot size for the cosmetic pass, which was made at the same speed. This pass flattened the weld crown formed during the previous pass (see detail A of Fig. 24).

Completed fuel elements were checked by visual and radiographic inspection. A ring gage was used to determine the flatness of the weld crown.

Example 475. Precise, Low-Heat Welds Made in an Aluminum Alloy Within ¼ In. of an Explosive Charge in a Fuze Assembly (Fig. 25)

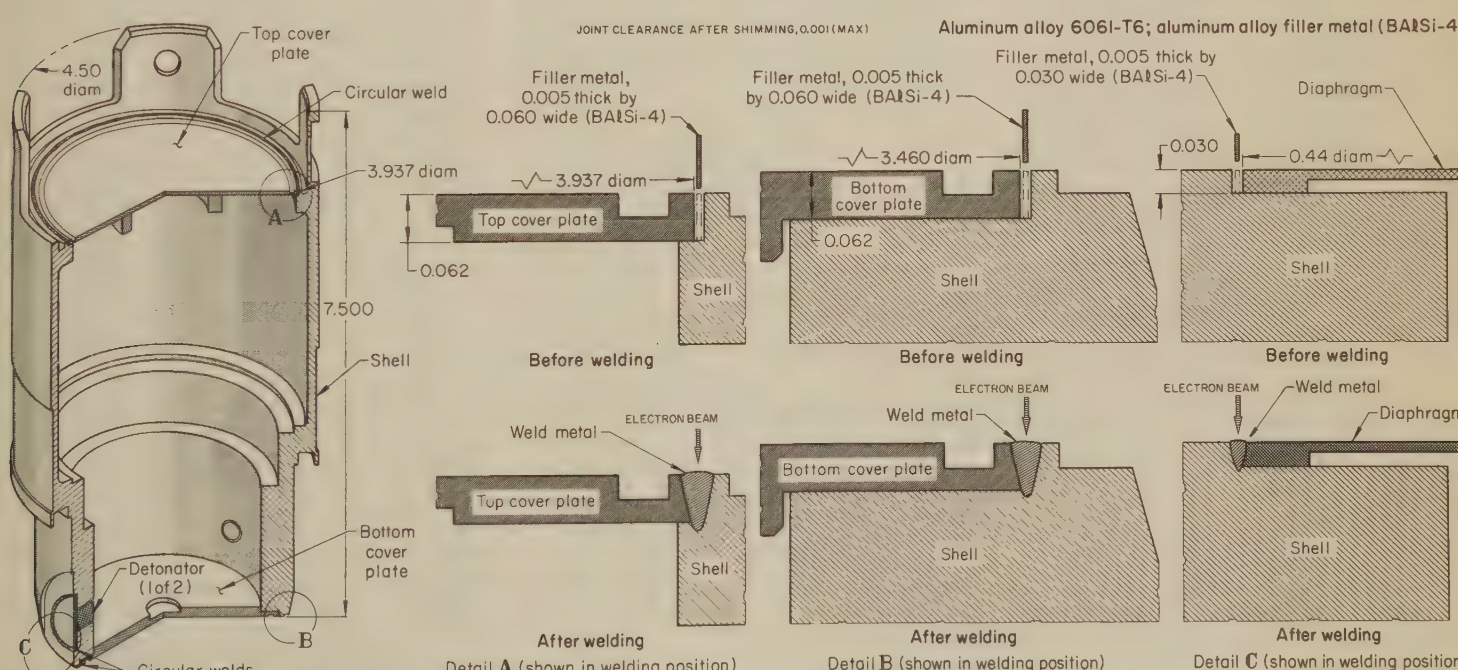
Electron beam welding was selected for the delicate final closure of the loaded fuze assembly shown in Fig. 25. The enclosure, which consisted of a shell, top and bottom cover plates, and two identical, oppositely located diaphragms, contained two stab detonators and two high-explosive (RDX) leads. Because the joints between the shell and the diaphragm were less than ¼ in. from the explosive, the safety of the operator and of the equipment depended on small, accurately placed welds with low total heat input, and careful handling.

Design considerations called for attaching the two cover plates and two diaphragms by controlled-penetration welds, of medium strength (18,000 psi) and capable of leak rates of less than 10^{-7} cu cm of helium per second at a difference in pressure of 1 atm. Preheating and postheating were not permitted. All of the components were made of aluminum alloy 6061-T6. Filler metal



Joint type	Butt	Welding power:	
Weld type	Square groove	Penetration pass	130 kv at 7 ma
Machine capacity	150 kv at 40 ma	Cosmetic pass	130 kv at 4 ma
Gun type	Fixed; with hairpin tungsten filament	Welding vacuum	10^{-4} torr
Vacuum-chamber size	36 in. in diameter by 144 in. long	Beam focal point:	
		Penetration pass	Sharp at work surface
		Cosmetic pass	Defocused
Maximum vacuum	10^{-5} torr	Beam deflection	None
Fixtures	Clamping tool; travel carriage	Working distance	12 in.
Pumpdown time	20 min	Welding speed	30 ipm (each pass)

Fig. 24. Aluminum-encased nuclear fuel element that was electron beam welded within 0.030 in. of the uranium-aluminum alloy fuel (Example 474)



Joint types	Circular corner and butt; rabbeted, self-backing	Filler metal	0.005-in.-thick foil of BAlSi-4	Beam oscillation(a)	0.010-in. diameter, at 1000 hertz(b)
Weld type	Square groove	Welding power(a):		Welding speed(a):	
Machine capacity	150 kv at 40 ma	Top cover (detail A)	130 kv at 6 ma	Top cover (detail A)	62 ipm (5 rpm)
Gun type	Steigerwald; fixed	Bottom cover (detail B)	110 kv at 5 ma	Bottom cover (detail B)	54 ipm (5 rpm)
Vacuum-chamber size	36 by 23 by 30 in.	Diaphragm (detail C)	130 kv at 4 ma	Diaphragm (detail C)	58 ipm (42 rpm)
Maximum vacuum	About 10^{-5} torr	Welding vacuum	10^{-4} torr or less (all welds)	Working distance	7½ in. (all welds)(c)
Fixtures	Universal chuck; turntable	Beam focal point	Sharp at surface (all welds)	Production rate	2.7 parts per hour

(a) Same for tack and final welds; weld time for tack welds was 0.05 sec. (b) Circular deflection. (c) Measured from top of chamber to workpiece.

Fig. 25. Aluminum alloy 6061-T6 fuze assembly and details of final-closure electron beam welds made between shell and cover plates and diaphragms. Low heat input and high precision of welds joining the diaphragms to the shells were highly critical, because the joints were less than ¼ in. from the explosive charge (not shown in illustration) in the shell at the time of welding. (Example 475)

was BAlSi-4 brazing alloy (12% Si), in the form of foil 0.004 to 0.006 in. thick cut to widths of 0.030 and 0.060 in. to fit tightly in the joint openings (see "Heat treatable alloys" and Example 493, on p 555, for discussion on crack sensitivity of alloy 6061-T6 in the absence of filler metal).

Weld width was about 0.020 in. on the diaphragms and 0.032 in. on the cover plates. Penetration was just beyond joint depth, to ensure consistent joint strength. At the joints between the shell and the covers, a circular recess was cut inside the joint (see details A and B of Fig. 25). The recess served to reduce the heat path to the cover, and the small lip allowed movement to help reduce residual stress from weld shrinkage on cooling. The reduced section of the diaphragms (about 0.010 in. thick) facilitated detonation.

After machining, the components were cleaned and degreased. Just before assembly for welding, the oxide was removed from welding surfaces by brushing with a small stainless steel wire or fiber glass brush. Dust was removed by wiping with a solvent, and care was taken to leave no fingerprints on the cleaned surfaces.

Each of the covers and diaphragms was assembled, fixtured, tack welded, and welded as a separate operation, the vacuum chamber being loaded and unloaded four times to complete one unit. Tack welding was used: (*a*) to eliminate the need for an additional costly fixture, (*b*) to prevent displacement of parts from thermal expansion during welding, and (*c*) to anchor the filler-metal strips against curling out of the joint during welding and to prevent distortion (curling) of the thin diaphragms and covers during welding.

Welding conditions for each of the operations are summarized in the table with Fig. 25. The sequence of operations for welding the top cover plate to the shell (detail A in Fig. 25), as described below, was typical for the four joints.

With the top cover plate shimmed tightly in place by filler metal, the subassembly, with its axis vertical, was chucked on a turntable inside the chamber. Using a 20-power telescope, the weld joint was checked for alignment, adjusted, and rechecked. A circular weight was placed on the cover to hold it in place for tack welding. Beam power and beam oscillation settings were made (these were the same as for the final welds), and the automatic weld timer was set for 0.05 sec. After vacuum pumpdown (2½ to 2¾ min), four tack welds were placed at 90° intervals by pressing the "on" switch, and rotating the part.

To make the final circular weld, the machine settings were adjusted as necessary, and the power supply was set for automatic upslope and downslope. Rotation was started and the "beam on" switch was pressed. Upon completing one revolution under welding power, the "beam on" switch was released, thereby actuating the downslope power mode, which carried the beam for a short distance, to taper the weld overlap. The overlap could be distinguished from the remainder of the weld only with difficulty. There was no evidence of the tack welds.

After the top cover was welded, the machine was unloaded. The bottom cover (detail B of Fig. 25) and the two diaphragms (detail C) were then welded similarly.

Testing of the completed units consisted of the leak-rate test described earlier. In addition, destructive tests were made on test pieces that simulated the weld areas of the fuze assembly. Periodically, three such samples were tension tested and examined macroscopically for weld soundness. Similar tests were also made on a regular sampling basis of one part out of twenty.

Welding of Thin Metal

Electron beam welding can be advantageous for joints in which at least one member is made of thin metal (less than 3/32 in. and as thin as 0.001 in.). Applications include instrument parts, instrument enclosures, pressure or hermetic seals, diaphragms, encapsulations, electrical connectors, and electronic devices, of various metals.

Table 3. Relation of Depth to Width (D/W) for Partial-Penetration Electron Beam Welds in Thin Sections(a)

Work metal	Thickness, in.	Weld depth, in.	Weld width, in.(b)	D/W for weld
Aluminum Alloys				
6061-T6	0.005	0.003	0.015	0.2
5052	0.010	0.005	0.012	0.4
	0.020	0.017	0.015	1.1
Stainless Steels				
17-4 PH	0.005	0.004	0.014	0.3
Type 301	0.010	0.006	0.011	0.5

(a) All welds were made in a high vacuum; chill tooling was in intimate contact with the underside of the work at the weld location. (b) Width of the weld at the crown, which was the greatest width for the gently radiused wide-angle V-shape welds.

The joint area must be heated to melting temperatures in joining thin sections, just as in joining thick sections, but the rate of heat transfer away from the joint is much lower, because of the reduced cross section. Hence, local heat buildup is greater, which increases weld width and decreases depth-to-width ratio. In addition, minimum beam spot size has a much greater effect on depth-to-width ratio in joining thin metal than in joining thick metal. The minimum usable beam spot size obtainable generally ranges from about 0.005 to 0.020 in. in diameter. Because of these conditions, depth-to-width ratio for full-penetration welds joining two sections thinner than about 3/32 in. usually does not exceed about 5 to 1, and may be less than 1 to 1.

When voltage, current, welding speed, and other conditions discussed in the section on Welding in High Vacuum have been optimized for a specific joint, use of a heat sink may still be necessary to avoid overheating thin material, depending on base-metal properties (melting point, specific heat, and thermal conductivity) and metal thickness. Best results usually are obtained by the use of copper chill blocks machined to fit the workpiece closely at the joint area. Fixtures made of other metals may be effective as chill blocks if contact area is sufficiently large and close to the heat source.

In the examples in this article, the thinnest section of work metal joined by electron beam welding was 0.010 in. thick (Examples 482 and 490).

Examples of welding metal thinner than 3/32 in. are:

Low-carbon steel	Ex. 467
HS-25	477
René 41	481
Copper alloys	482
D-6ac	486
Cb-752	490
Tantalum alloy	491
Aluminum alloys	493 and 494

Joining Thin Sections to Thick Sections. In joining thin sections to thick sections by electron beam welding, the joint is usually designed so that the thick member serves as a heat sink for the thin member, and the point of beam impingement is slightly removed from the thin metal. When these precautions are taken, welding behavior and heat dissipation are generally the same as in welding thick sections under similar conditions. Depth of penetration in the thicker section is usually made only slightly greater than the thickness of the thin section.

Six examples in this article deal with the welding of thin to thick sections:

1020 to 1140 steel	Ex. 468
Type 304 stainless steel	476
17-4 PH stainless steel	489
Aluminum alloy 2024-T4	495
Aluminum alloy 5052	492
Aluminum alloy 6061-T6	475

Even with the aid of the heat-sink capacity of a thicker member, heat input by arc welding often cannot be localized sufficiently and controlled closely enough to avoid damage to metal of foil thickness. In the example of welding type 304 stainless steel that follows, in which 0.002-in.-thick foil was sandwiched between 0.040-in.-thick sheet and the edge of a 0.100-in.-thick cylinder wall, gas tungsten-arc welding was replaced by electron beam welding to eliminate excessive foil melting.

Example 476. Melt-Through Welding of 0.002-In.-Thick Foil Between 0.040-In.-Thick Sheet and the Edge of a 0.100-In.-Thick Cylinder Wall (Fig. 26)

A rupture-disk assembly (Fig. 26) designed for gas-pressure relief consisted of three components: (*a*) a 2-in.-diam nozzle of 0.100-in.-thick type 304 stainless steel attached to an outer pressure vessel (not shown); (*b*) a 0.002-in.-thick cupped rupture disk of type 304 stainless steel; and (*c*) a 0.040-in.-thick cap, also of stainless steel, containing an off-center flued-in hole with downward-pointing knife edges.

The three components were joined by a single weld that was required to have a leak rate of less than 10^{-8} cu cm per second when tested with a helium mass spectrometer. When pressure in the nozzle exceeded the design limit, the cupped rupture disk reversed its shape from concave to convex, puncturing itself against the knife-edge of the cap. Leaktightness, rather than high tensile strength, was the welding objective. The material was selected for long maintenance-free service, rather than for resistance to a corrosive environment.

Originally, the components were joined in one pass by automatic gas tungsten-arc welding, using the design shown in detail A, original method, Fig. 26. A circular groove was cut in the nozzle wall to help localize the weld bead, which was made without filler metal. Light pressure was applied at both ends of the assembly to hold the parts in alignment for welding.

This procedure resulted in numerous rejects because of leaks. Often, difficulty was encountered in getting the disks to lie absolutely flat on the joint surface. The 0.002-in.-thick rupture disks, having been blanked and formed in the work-hardened condition, were tough, springy and sometimes burred. As a result, they occasionally were burned back, instead of being fused into the weld bead, causing leaks. It was usually impossible to salvage this type of defect by rewelding.

To eliminate these difficulties, the operation was converted to electron beam welding, even though initial equipment and tooling costs were high. The equipment was also profitably used for other applications (see Example 499).

The electron beam welding machine used for this application had a relatively large vacuum chamber with full-width doors, to facilitate loading and unloading of large, multiple-part fixtures. The holding fixture used had 56 receptacles to position and in-

dividually rotate 56 assemblies under a stationary gun. The fixture was mounted on a horizontal table equipped with x-y motion control to permit optical alignment of the beam for welding each part in turn.

Each assembly was fitted into a cylindrical receptacle, or pot, that was equipped with a hold-down ring that forced the periphery of the disks and caps into close alignment, as shown in detail A, improved method, Fig. 26. A melt-through, or spike, weld was made, rather than an edge-flange weld at the periphery.

With this setup, the blanking and forming operations on the disks could be allowed the more realistic tolerance of ±0.002 in. on flatness. The electron beam was angled slightly, as shown, and was positioned close to the hold-down ring so that, in the event of a leak, the joint could be rewelded by running a second weld just inside the first weld.

The weld-localizing groove needed for the original gas tungsten-arc method was eliminated, and the electron beam melt-through weld was made at a heat input of 0.25 kj per inch of weld length, which was much lower than for arc welding. The hold-down ring provided only a slight chill effect, but enabled the nozzle body to function effectively as a heat sink.

Welding conditions for the electron beam process are given in the table accompanying Fig. 26.

Welding results from the electron beam procedure were good. Joint defects of all types dropped to 3%, and most of the rejects could be salvaged by rewelding. A production rate of 44½ assemblies per hour was a significant improvement over the original arc method.

Partial-Penetration Welds. The precise control of heat input obtainable in electron beam welding permits partial-penetration welds having uniform depth to be made in metals as thin as 0.010 in., and sometimes less.

Work-metal thickness must be uniform, and workpiece, fixture arrangement, and dimensions must be selected to provide a constant rate of heat loss adjacent to the path of the weld along its entire length, with special provisions made for weld starting and stopping. Beam power, focus, and workpiece travel speed must be closely regulated to minimize variation in penetration.

For the closest control of penetration, both beam power and focus can be regulated by sensitive, fast-response closed-loop servomechanisms or feedback controllers, and workpiece travel speed can be held within extremely narrow limits by precision, mechanical worktable traverse or by rotary-motion systems. To compensate automatically for the effect of any variation in voltage on focus, the servomechanism regulating the beam focus can be coupled to the voltage supply by solid-state devices that have a response time of less than 17 microseconds.

Partial-penetration welds in thin metal are not subject to root voids, root porosity, or cold shuts, which are defects frequently encountered in partial-penetration welds in thick metal, because such welds in thin metal have relatively low depth-to-width ratios and a wide-angle V-shape with a gently radiused bottom.

Data on the relation of depth to width for high-vacuum partial-penetration welds in thin sections is given in Table 3. The ratio of depth to width is lower for the welds in the thinner sections. Penetration was from 50 to 85% of the work-metal thickness, and all welds were made with chill bars in intimate contact with the underside of the work at the weld location.

Depth of penetration generally varies 10 to 15% from a mean value for a work thickness of about 0.020 in., and the percentage variation is greater for welds in thinner metal. Accordingly, partial-penetration welds are not ordinarily made in metal thinner than about 0.010 in. Beam oscillation is sometimes used to smooth out variation in penetration, but such oscillation must be controlled closely in order to be effective.

In the example that follows, low beam power and circular oscillation were used in producing sound partial-penetration welds 0.030 to 0.045 in. deep and 0.026 in. wide at the crown (average depth-to-width ratio of 1.4, and 50 to 75% penetration) in 0.060-in.-thick HS-25 heat-resisting alloy.

Example 477. Partial-Penetration Welding of Thin-Wall Joints in HS-25 Rocket-Engine Nozzles (Fig. 27)

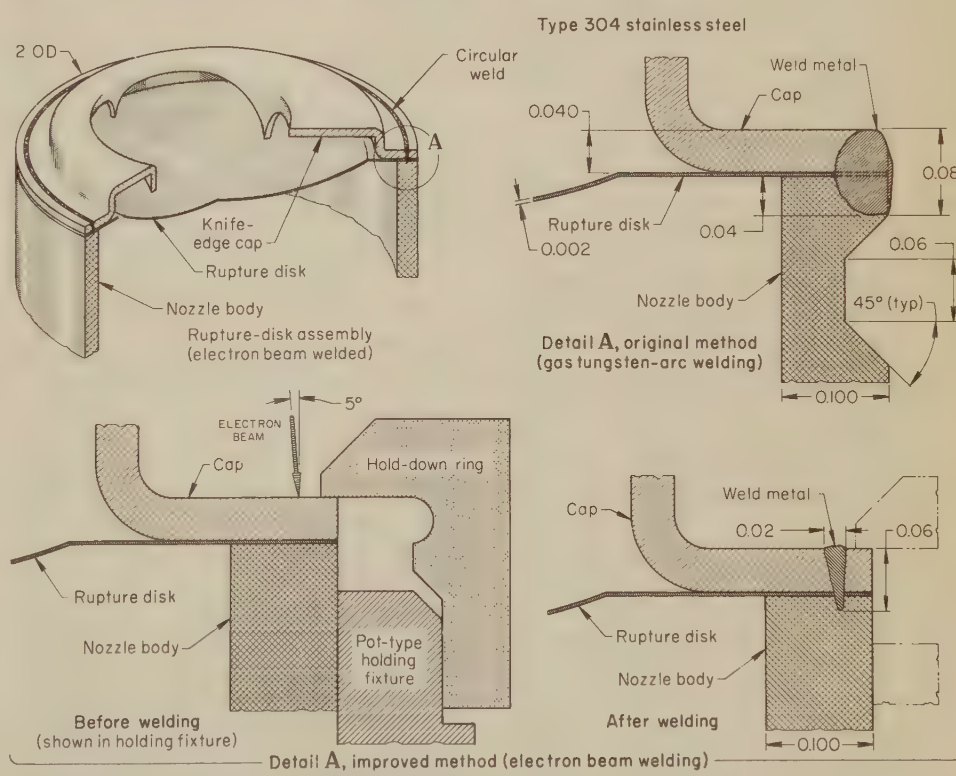
Proper functioning of the rocket-engine nozzle assembly shown in Fig. 27 required a welding procedure that would: (*a*) avoid distorting the critically aligned parts; (*b*) avoid internal spatter or melt-through to disturb flow characteristics; and (*c*) minimize heat effects in the base metal. Gas tungsten-arc welding was considered, but could not provide the low, accurately controlled, localized heat input needed for freedom from cracking and distortion. Partial-penetration electron beam welds finally met the requirements, with special attention given to joint preparation.

A rabbeted, self-backing, square-groove butt joint, as shown in Fig. 27, detail A, was selected to ensure a tight fit for accurate alignment of the two joints and to facilitate partial penetration into the thicker member.

When trial welds were made to determine machine settings, it was found that the alloy used, cobalt-base alloy HS-25, although heat resistant, was highly susceptible to microcracking during cooling from welding temperature. The cracking was promoted by loose fit-up, which was traced to the procedures used in machining, annealing, and mechanical cleaning.

For the trial welds, the joint edges had been machined with the metal in the annealed condition, using single-point tools. Because HS-25 alloy strain ages at 700 to 1100 F, as well as from cold work, the manufacturing sequence was changed so that annealing was done after rough machining with form tools, and only a light finish cut was taken after annealing and before welding. The slight bevel shown at the inside corner of the joint in Fig. 27, detail A, aided in assembly for welding and was also a check on penetration, during radiographic examination.

All mechanical cleaning methods, such as filing, scraping and wire brushing, were avoided. Joints were cleaned chemically and rinsed in acetone. Extra care was taken in handling the parts to avoid nicking or breaking the edges.



Conditions for Electron Beam Welding

Joint type	Circular, three-piece corner	Welding vacuum	5×10^{-5} torr
Weld type	Melt-through (spike)	Pumpdown time	10 min
Machine capacity	50 kv at 250 ma	Working distance	1.5 in.
Gun type	Diode; fixed during welding	Beam focal point	Sharp at work surface
Vacuum chamber	Steel; 54 by 48 by 48 in., with full-width end doors	Beam spot size	About 0.020-in. diameter
Fixtures	56-piece holding tool with individual rotation; table with x-y motion	Welding speed	100 ipm
Welding power	26 kv at 16 ma	Number of passes	One, plus 30° downslope
		Setup time	48 min
		Production rate	44½ pieces per hour

Fig. 26. Stainless steel rupture-disk assembly, originally joined by gas tungsten-arc welding, for which change to electron beam welding increased production rate and eliminated fit-up problem that caused burning of 0.002-in.-thick foil. Joint details of both gas tungsten-arc and electron beam welding are shown. (Example 476)

To reduce shrinkage stresses, joint fit-up tolerances were tightened. Allowable joint mismatch was held to ±0.002 and root-opening tolerances were set at zero to 0.004 in. Although the slip joint appeared tight, some loosening occurred during welding, and so the joint was tack welded.

The beam was circularly oscillated over an 0.015-in. diameter at 500 hertz, to avoid joint underfill at the weld surface. This technique was preferred to the use of a cosmetic pass with a defocused beam, which had caused distortion and cracking in welds on other alloys of this type.

The weld was made in one pass, with a short overlap to permit smooth downslope of the beam power. Downsloping the beam power helped to avoid crater cracks at the beginning of the overlap. No preheat was used in this application, nor was chill tooling used. Although postweld annealing would have been desirable, it was not done because it would damage the catalysis chamber. The completed weld is shown at the lower right of Fig. 27.

When all of the foregoing precautions and techniques were adopted, good welds resulted. Welding conditions are given in the table with Fig. 27.

Special Welds. Thin sections are frequently electron beam welded in special shapes, as dictated by the design of the weldment and the need for control of heat input in welding. In some cases, joint-design criteria, as ordinarily applied, must be compromised to a small extent in order to accomplish such welds. In Example 469, 0.005-in.-thick foil was placed between 0.060-in. stock; Examples 481 and 482 describe multiple-tier welding; and in Example 485 a filler-metal wire was placed in a bevel groove atop a 0.010-in.-clearance joint to make a seal weld.

Welding of Thick Metal

For joining thick sections, electron beam welding in a vacuum has three principal advantages over other welding processes:

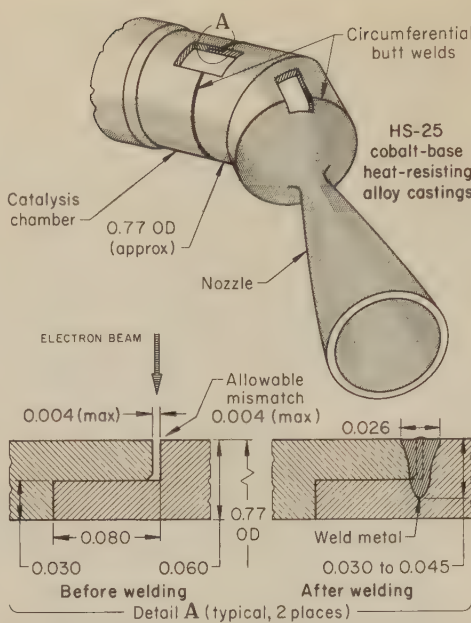
1 Much deeper penetration can be obtained in a single pass. Extremely narrow, only slightly tapered welds and small heat-affected zones can be produced.
2 For joints on most weldable metals, no filler metal is needed. Where a filler metal is required, the quantity is usually very small.
3 Joints have closely fitted parallel groove faces requiring no edge preparation, instead of V-grooves or U-grooves.

The disadvantages of electron beam welding for joining thick metal are those usually associated with this process: high equipment cost, size limitations imposed by the dimensions of the vacuum chamber in which the work must be placed, and the time needed for evacuating the chamber.

Nonvacuum electron beam welding is not ordinarily used for welding thick metal and is seldom practical for making welds deeper than about ½ in.

Deep welds made in a vacuum are usually narrow; weld width for penetration deeper than about ¼ in. is typically about ⅕ to ⅒ of the section thickness, except for a somewhat greater width at the crown of the weld. Welds may be either full-penetration or partial-penetration.

Effects of Pressure. Penetration capability is greatest for electron beam welding in high vacuum. The effect of the pressure at which the welding is



Joint type	Circumferential butt; rabbeted, self-backing
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald; with tungsten filament
Vacuum chamber	Lead-lined steel; 36 by 23 by 23 in.
Maximum vacuum	10^{-5} torr
Fixtures	Three-jaw chuck; rotating spindle
Welding position	Horizontal rolled
Welding power	100 kv at 2.2 ma
Welding vacuum	5×10^{-5} torr
Pumpdown time	5 min
Beam oscillation	0.015-in. diameter, at 500 hertz
Working distance	6 in.
Power density of beam	1.25 megawatts per square inch
Welding speed	39.7 ipm (16.4 rpm)
Number of passes	One, plus overlap

Fig. 27. Small HS-25 heat-resisting alloy rocket-engine assembly consisting of catalysis chamber, 45° elbow, and thrust nozzle, which were joined by partial-penetration electron beam welding to prevent distortion, maintain smooth interior, and avoid cracking (Example 477)

done on the maximum penetration obtainable in steel at 9-kw beam power is shown by the following data, which are typical for commercial equipment:

Type of system	Pressure at workpiece, torr	Penetration (max), in.	Welding speed, ipm
High vacuum	10^{-4} to 10^{-5}	3½	4
Medium vacuum	10^{-1}	2½	6
Nonvacuum	760	½	20

Full-Penetration Welds. In welding carbon steel, single-pass, full-penetration, vacuum electron beam welds are made commercially in thicknesses ranging up to approximately 2 in. Production electron beam welding has been done on aluminum alloy plate 6 in. thick, and 9-in.-thick aluminum alloy sections have been welded experimentally under near practical conditions.

Examples in this article that deal with full-penetration welds in thick sections are as follows:

Type 410 stainless steel	Ex. 466
Duplex metal	471
10B22 to 1040 steel	473
Invar to Mn-18Cu-10Ni	478
4340 steel	503
AMS 6265 steel	504

Two-Pass Full-Penetration Welding. Penetration can be nearly doubled by making two passes, one on each side of the work, but cold shuts, voids and porosity are encountered at the root of the second weld unless conditions are adjusted for the pass made on the second, or back, side. A broader second-side weld with a larger radius at the root helps to reduce the incidence and severity of these defects, but they often remain a problem.

The example that follows describes the full-penetration welding of ⅝-in.-thick metal in two passes, one on each side, in welding together large billets of unlike metals for subsequent rolling into thin bimetal strip.

Example 478. Full-Penetration Welding of a ⅝-In.-Deep Joint Between Unlike Metals in Two Passes, One on Each Side (Fig. 28)

Electron beam welding was used to join massive bars of Invar and a manganese-copper-nickel alloy into bimetal billets that were rolled into thin strip for use in thermostats (Fig. 28). Nominal composition and room-temperature coefficients of thermal expansion for the two alloys, which show a wide difference, were as follows:

Alloy	Nominal composition	Expansion, micro-in./in./°C
Invar	36 Ni, 64 Fe	0.877
Mn-Cu-Ni	18 Cu, 10 Ni, 72 Mn	28.5

Normally, bimetal billets were joined by furnace brazing, but an alternative method was sought for joining this combination because of difficulties in brazing and an undesirably low production rate.

A uniform metallurgical bond over the entire interface was required, since after bonding, the billets were hot rolled and then cold rolled to final thicknesses of 0.005 to 0.060 in., depending on the application.

Bars of the two metals were machined to the dimensions shown in Fig. 28 and the surfaces to be welded were ground to a finish of 32 micro-in. max, in preparation for joining. Initial thicknesses of the bars to be joined were 1½ in. for the manganese alloy and 1 in. for the Invar, to allow for lower hot strength and greater reduction of the manganese alloy during hot rolling. Final thickness ratio was 9 to 11 (manganese alloy to Invar).

The first method tried as an alternative to furnace brazing was diffusion welding, because large, vacuum hot-pressing furnaces were available in which many pieces could be bonded in a single load. However, good pressure bonds were difficult to obtain, even in small laboratory furnaces at vacuums less than 5×10^{-2} torr, because of the ease with which the manganese alloy oxidized.

Several attempts were made to produce the diffusion bond in a production furnace having a normal operating vacuum of about 3×10^{-1} torr. No filler metal was used. Results obtained after hot and cold rolling the bonded billets were not satisfactory. Temperature seemed extremely critical (1900 F +10, −20 F), and control within this narrow range was not feasible on a production basis.

When electron beam welding was tried, excellent bonding results were obtained. The two bars were clamped in heavy-duty vises and C-clamps on a traversing table in the vacuum chamber, with the joints in the vertical position as shown in section A-A in Fig. 28. Using the conditions given in the table with Fig. 28, a 3-in. depth of penetration was achieved in each pass, which provided full penetration with an overlap of ⅝ in.

One of the problems encountered was that, when the billet was removed from the clamping fixture to turn over for making the second weld, the heated piece bowed. Rather than attempt to reclamp the billet in this condition, it was allowed to return to room temperature and thereby to resume its original shape.

There was some concern over maintaining uniform weld width through the depth of the joint, because nonuniform weld width might ultimately result in irregular bimetal deflection. However, except for a depth of about ½ in. at each surface where the electron beam impinged, the weld width was held to ⅛ in. +0, −1⁄32 in. After reducing the 2½-in.-thick billets to an average strip thickness of 0.020 in., the weld fusion zone could not be identified.

After four bimetal billets were welded by this procedure, the electron beam welding procedure was accepted as an alternative method to furnace brazing.

Partial-Penetration Welding. Welds that do not penetrate completely through the work metal are satisfactory in many applications in welding thick metal; joint design and product requirements often rule out full penetration.

Examples in this article that deal with partial-penetration welds (0.30 to 1.5 in.) in thick sections and the work metals involved are as follows:

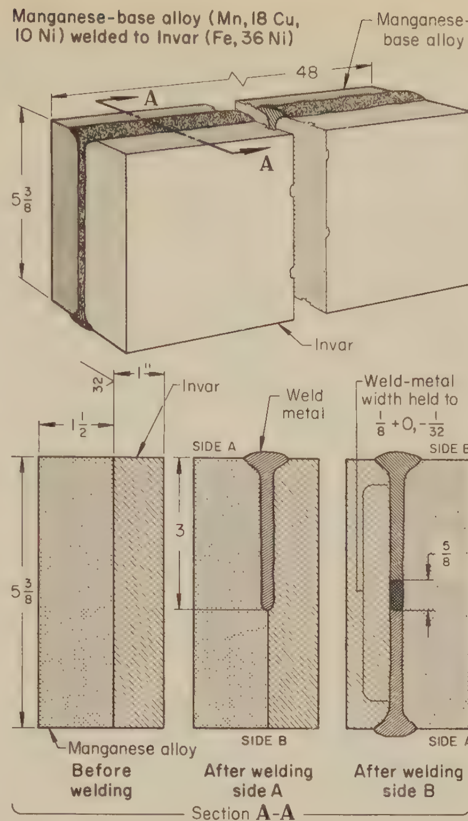
4340 steel	Ex. 464
AMS 6260 steel (9310)	505
H11 tool steel	488
Aluminum alloy 356	480
Copper alloy 175	502
Magnesium alloy AZ91C	479
Titanium alloy (6Al-4V)	496

Additional partial-penetration welds that had a depth of at least ⅛ in. are described in Examples 465, 468, 470, 472, 483, 487, 496 and 499.

Problems and Defects. In making vacuum electron beam welds ⅛ to ½ in. deep in weldable metals, weld quality is ordinarily equal to or better than that of arc welds in the same metal. Special precautions are needed to avoid certain types of defects in welds about ½ in. deep or deeper. Fusion-zone porosity, gas pockets, and cold shuts are more serious problems than in arc welding, particularly in deep welds.

Reducing the welding speed usually helps to reduce porosity and gas entrapment. Extreme care in cleaning the work metal may be necessary where the problem is severe. When defects are found near the root of the weld, they can be avoided or minimized by any adjustment of welding conditions that broadens the weld and increases the radius of the weld at the root. Sometimes, the joint can be designed so that any root defects are in a noncritical region, or in integral or separate backup metal that will be machined away after welding.

As in arc welding, cold shuts (incomplete fusion) are sometimes encountered at the root of a deep partial-penetration weld or of a full-penetration weld that has a poorly fitted backing strip. These defects are troublesome because they are difficult to detect. Normally they cannot be detected by radiographic methods. Ultrasonic testing can detect the larger cold shuts. Many cannot be observed on roughly polished macrosections of electron beam welds, but require a metallographic polish and examination at a magnification of at least 100 diameters for detection. Cold shuts can usually be avoided or minimized by reducing the welding speed or by otherwise changing conditions so as to broaden the weld and increase the radius of the weld at the root.



Joint type	Edge
Weld type	Double square groove
Machine capacity	150 kv at 200 ma
Gun type	Fixed
Vacuum-chamber size	56 by 56 by 114 in.
Fixtures	Vises; C-clamps
Welding power	150 kv at 170 ma
Welding vacuum	5 × 10^{-4} torr
Beam focal point	¼ in. below work surface
Welding speed	18 ipm

The welded bimetal billets were later reduced by hot and cold rolling to make 0.005 to 0.060-in.-thick bimetal strip for use in thermostats.

Fig. 28. Three stages in two-pass (one per side) electron beam welding of Invar and manganese-copper-nickel alloy for a narrow, full-penetration edge weld over a bond area of 5⅜ by 48 in. (Example 478)

Poor fit-up or excessive joint gap can cause excessive shrinkage, underfill, undercut, voids, and cold shuts. Joint gap should not exceed 0.010 in. for narrow welds deeper than about ½ in. in most metals, although sound welds have been obtained using joint gaps of 0.030 in., by use of a procedure that increased weld width to 0.275 in. MIL-W-46132 requires a maximum separation of 0.004 in. for welds deeper than ⅛ in.

Welding with the beam at a slight angle to the joint is helpful in avoiding defects related to poor fit-up, but may increase weld width excessively and require an unduly low welding speed for deep welds.

Excessive mismatch can cause defects of the same general types as poor fit-up; mismatch limits depend on joint design and dimensions, and operating conditions. Weld quality in joining thick sections is ordinarily unaffected by changes in surface roughness of the joint faces between about 63 and 1000 micro-in.

A problem that is to some extent unpredictable and inconsistent in making electron beam welds deeper than about ½ in. is arc-outs, or sudden failures of electron emission during welding. However, problems of arc-out have decreased with the newer machines and experience accumulated in operation.

Work-metal composition and quality also influence arc-outs, which are more frequent when welding materials with low vaporization points, or when welding materials susceptible to outgassing in a vacuum or those that contain nonmetallic inclusions.

Use of Filler Metal

Fusion of closely fitted groove faces generally provides sufficient weld metal, or extra metal is provided where necessary by including extra stock thickness or integral shoulders or lips in the joint preparation (see the discussion of welds using integral filler metal, page 524).

Where product requirements or other circumstances prevent the use of a joint preparation and welding conditions that will provide sufficient weld metal, filler metal is added. This was done in welding the type 304 stainless steel assembly of Example 485.

Prevention of Cracking. Filler metal (shim stock) additions can prevent cracking in electron beam welds in a crack-susceptible metal or combination of dissimilar metals. It may be needed even when joint design, fit-up and operating conditions are selected to achieve minimum joint restraint and residual stress. In other applications, the use of preplaced filler metal can provide weld metal that is less brittle than would be obtained by welding a base metal (or metals) alone.

Among the base metals for which added filler metal is often required are heat treatable aluminum alloys 6061, 6063 and 6066, free-machining steels, and other free-machining alloys. Example 468 describes the use of Hastelloy W filler metal in welding 1140 free-machining steel to 1020 steel. In Examples 475, 493 and 494, in which 6061-T6 aluminum alloy was electron beam welded, brazing filler metal BAlSi-4 was used to prevent cracking.

Many combinations of dissimilar metals that are susceptible to cracking when welded directly, usually because of the formation of brittle intermetallic phases, can be electron beam welded with the aid of filler metal that has a composition compatible with both metals of the combination (see the section on Joining of Dissimilar Metals, page 559).

Preventing Porosity. The electron beam welding of rimmed steel without filler metal ordinarily results in severe porosity in the weld, even when welding speed is slow and other conditions are selected to increase the time during which gas can escape from the molten weld metal. Inserting a filler metal that contains a deoxidizer such as aluminum, manganese or silicon helps to minimize porosity.

Copper alloy 110 (ETP copper) and other types of copper that do not contain residual deoxidizers also produce porous welds when joined without filler metal, but sound welds can be made with the aid of nickel filler metal or a deoxidizing filler metal.

In welding terminals in Example 482, the copper core of each terminal was clad on both sides with BCuP-5 filler metal to provide deoxidation.

Preplacement of Filler Metal. The technique most frequently used for the addition of filler metal in electron beam welding, especially for deep welds, is preplacement. A shim of filler metal, usually of foil thickness, can be inserted between the groove faces when the joint is assembled for welding, as in Examples 475, 493 and 494, or a wire or other suitable shape can be preplaced over the joint, being held in position by tack welding, if necessary, as in Examples 468 and 485.

Filler-Wire Feeding. Electrically operated filler-wire feeding systems that are modifications of wire-feed equipment used in gas tungsten-arc welding, or specially designed electron beam wire feeders, are sometimes used in the vacuum chamber.

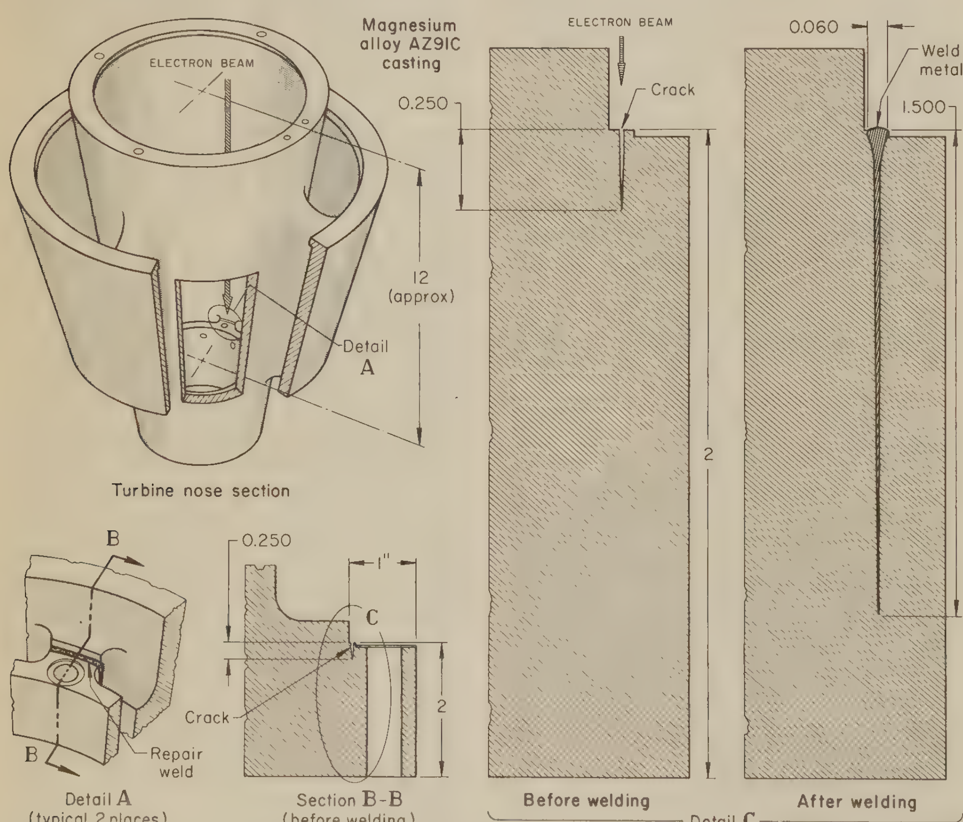
Usually, filler-wire feeding will not help in joining incompatible metals unless they are very thin.

The design of the wire-feeding nozzle and the technique with which it is used are important in guiding the wire so that it intercepts the electron beam. Failure to intercept the 0.010-to-0.030-in.-diam beam results in irregular application of filler metal. Any filler metal inserted into the beam path absorbs energy and affects penetration.

The wire-feeding nozzle is normally held as close to the weld puddle as is possible without damage to the nozzle, and the wire is directed into the forward edge of the puddle. The tip of the nozzle should be made of a heat-resistant material and should be coated so as to prevent molten weld metal from adhering to it if inadvertent contact is made. The nozzle is usually pointed in the direction of workpiece travel.

Wire-Feeding Equipment. Several design features are desirable in a wire feeder for electron beam welding. These include means of making positioning adjustments from outside the vacuum chamber during welding, such as: changing the proximity of the nozzle to the weld puddle, changing the angle of incidence between the workpiece and nozzle, and controlling the movement of the wire relative to the beam to ensure accurate interception.

A simple, variable-resistance, controlled motor drive is ordinarily satisfactory, as a 10% variation in wire speed causes no adverse effect other than a slight variation in weld width. It is desirable to be able to control the timing so that wire feed can be started and stopped independently of the beam and table. Being able to adjust the timing of the wire feeder eliminates sticking of the wire to the workpiece at the end of the weld.



Weld type ....Crack repair	Welding power ....140 kv at 40 ma
Machine capacity ....150 kv at 40 ma	Welding vacuum ....2×10^{-4} torr
Gun type ....Triode; fixed	Working distance ....15 in.
Maximum vacuum ....5×10^{-5} torr	Beam focal point ....¼ in. above work surface
Vacuum-chamber size ....25 by 22 by 28 in.	Beam spot size ....About 0.030 in.
Fixtures ....Track-guided carriage; holding clamps	Welding speed ....30 ipm
	Preheat and postheat ....None

Fig. 29. Nose section of a turbine engine showing method of repairing two fatigue cracks by electron beam welding. Limited access and likelihood of distortion precluded the use of other welding processes. (Example 479)

Vibrating the nozzle at subsonic rates promotes flow of molten metal into the weld joint and results in less wire sticking at the end of the weld.

Welding Technique When Feeding Filler Wire. The wire-feed rate is usually set at approximately the same rate as the welding speed. Beam power must be sufficient to melt the wire as fast as it is fed. The wire diameter is selected so as to provide 1.25 times the volume of filler metal needed to fill the joint cavity. Where needed, backing strips or rings are used to prevent loss of molten weld metal.

The filler metal can be deposited during the weld pass, using a low welding speed to allow time for the molten metal to fill the joint gap, but for deep welds it is preferably deposited in a separate pass.

If cracking is a problem, another method used on thin metal is to deposit filler metal on the joint, and then make the welding pass to distribute the filler metal more effectively.

Tack Welding

In fixturing work for electron beam welding, clamping is often supplemented or replaced by tack welding, which is usually done with the electron beam. Fixturing time and cost are often substantially reduced by the effective use of tack welds.

In some applications, selection of the tack welding procedure is critical, to avoid unacceptable variation in the shape and dimensions of the final weld bead, and to avoid root porosity or cold shuts. Reduced power and other special operating conditions are often used.

Techniques. Perhaps the most common technique is to make one or more suitably spaced tack welds at full or reduced beam power before making the welding pass. For circular or circumferential welds, one or more tack welds are usually made, as was done in Examples 465, 469, 470, 477, 489, 492, 496, and 501. Melt-through (spike) tack welds were used on the straight-line lap joints described in Example 502.

A shallow seal pass at reduced beam power can also be made along the full length of the joint to keep the workpieces aligned, to be followed by the full-power penetration pass, as in Example 484. For some applications, it is convenient to leave occasional unwelded gaps as an aid for tracking the joint during the penetration pass.

Electron beam tacking can hold preplaced filler metal in position in or over a joint, as in Examples 475 and 494; resistance spot welds were used to hold filler-metal wire in position over the joint in Examples 468 and 485. Arc spot welds can be used for tacking some types of work (see Example 467).

Welding of Poorly Accessible Joints

One of the advantages of electron beam welding is the capability of reaching into areas lying deep within narrow openings. This is accomplished by virtue of the electron beam having a small diameter, long working distance and, frequently, the capability of

being projected at an angle. Many joints that are inaccessible for welding by other processes can be electron beam welded. This capability is used both in fabrication and in repair work. It is especially useful in salvaging intricate castings.

Workpiece Requirements. For limited-access welding, the workpiece must satisfy three general requirements: (*a*) the weld area must be on a line-of-sight path from the beam source; (*b*) there must be sufficient sidewall clearance to avoid beam-fringe interference; and (*c*) the beam path must be free of magnetic fields.

Beam characteristics that determine applicability of electron beam welding to poorly accessible joints are beam diameter and the working distance, or effective beam length available between the exit end of the beam transfer column and the work. These characteristics in turn depend on the beam power used, which is selected to produce the desired penetration, and on beam focal length, which is influenced by the design of the gun, the chamber and the focusing coil.

Sidewall Clearance. Parts intended for fabrication by electron beam welding can often be designed with sufficient sidewall clearance for the beam power required. Where insufficient sidewall clearance exists in repair welding, lowering the beam power or slightly changing the angle of incidence of the beam will often avoid interference. In repair welding, tests should be made on simulated joints, using the same type of work metal and the required beam power, rather than to risk damaging difficult-to-replace parts.

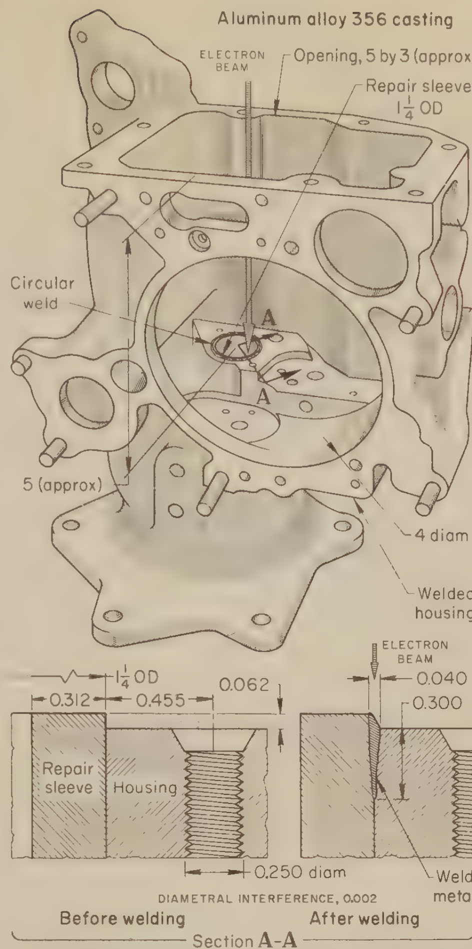
Where close sidewall clearances are involved, it is especially important to avoid magnetic fields, which can cause damage to the part by deflecting the beam. A test run on low power is commonly used to detect beam deflection; however, allowance must be made for the increase in deflection at full welding power. Magnetically soft materials with induced magnetism can usually be demagnetized with magnetic-particle inspection equipment or with coils.

Minimum beam clearance for making welds close to magnetic metal that projects above the work surface at the joint is given on page 523 (top of column 3) and in Fig. 7.

Examples of Practice. The use of electron beam welding to make repair welds at sites deep within finish-machined castings, where access was too limited for repair by any other method, is described in the next two examples:

Example 479. Repair of Cracks in a Magnesium Alloy AZ91C Casting (Fig. 29)

The long-focal-length capability of the electron beam simplified repairing of fatigue cracks in the nose section of a magnesium alloy turbine casting. The casting, as shown in Fig. 29, had straight, partially penetrating cracks running across the ligaments connecting the body to a bearing support. The cracks were located approximately 12 in. down in the nose, in a narrow area where access by any other welding process was virtually impossible. In addition, because the nose section was finish machined and matched to its counterpart, neither distortion nor further machining to overcome distortion could be tolerated.



Joint type	Circular butt
Weld type	Square groove, integral filler-metal shoulder
Machine capacity	150 kv at 40 ma
Gun type	Triode; fixed; with long focal length
Vacuum-chamber size	25 by 22 by 28 in.
Maximum vacuum	5×10^{-5} torr
Fixtures	Holding clamps; turntable
Welding power	150 kv at 10 ma
Welding vacuum	2×10^{-4} torr
Working distance	10 in.
Beam focal point	¼ in. above work surface
Beam spot size	About 0.020 in.
Beam oscillation	None
Travel speed	30 ipm (6 rpm)
Number of passes	One, plus 60° overlap
Total machine time	20 min(a)

(a) Includes part setup, beam alignment, pumpdown, weld traverse, and unloading

Fig. 30. Completely machined aluminum alloy housing that was initially rejected because of an oversize bore, but later salvaged by inserting a repair sleeve and welding it in place by electron beam welding. Access to the joint was too limited for other welding processes. (Example 480)

Preparation for welding consisted of flushing the cracked areas with methyl ethyl ketone. The cracks were not chipped out, and no filler metal was required. The casting was positioned on a traveling table with the work surface located 15 in. below the electron gun. Beam alignment was checked optically for each weld traverse before welding power was turned on, to ensure adequate clearance of projections.

Beam power was selected to penetrate well beyond the apparent crack depth, but not through the section. Beam focal point was adjusted at ¼ in. above the work surface, the slight defocus serving to minimize weld porosity. The cracks were sufficiently straight to be traversed automatically in a single pass, requiring only a few seconds. Using the welding conditions shown in the table with Fig. 29, narrow welds were obtained with heat input low enough to preserve machining tolerances. Completed welds were examined by radiography to ensure freedom from gross porosity. The casting was returned to service at a small fraction of the cost of replacement.

Example 480. Repair of an Oversize Bore in an Aluminum Alloy Casting (Fig. 30)

A finish-machined 356 aluminum alloy housing, which represented an investment of more than $500, was rejected because of an oversize bore at a site deep inside. The casting was salvaged by fitting and welding a repair sleeve in the bore.

Electron beam welding was suited to the requirements of the salvage operation, producing a weld 0.040 in. wide (max) at the repair site, which was about 5 in. below the face of the top flange. The electron beam, projected from outside the housing, could just clear the internal obstructions; access was too limited for welding by other processes. There were no magnetic fields in the workpiece to cause unwanted beam deflection, and the low heat input produced no noticeable distortion.

Figure 30 shows an enlarged view of the welded repair sleeve; the edges of two tapped holes were only 0.33 in. from the centerline of the weld. A partial-penetration weld only 0.300 in. deep was made at the joint. The underside of the joint was inaccessible for welding. The single weld was strong enough that the sleeve could be finished and the cast housing could fulfill its operating function.

The repair sleeve was machined from aluminum alloy 356 with a diametral interference of 0.002 in. max for a press fit. After degreasing, the sleeve was fitted to the bore with a 1/16-in. projection to provide metal for the joint and fillet reinforcement.

After setup, beam alignment and pumpdown, the actual weld was made in about 10 sec, using the settings shown in the table with Fig. 30. This procedure not only saved the cost of a new housing, but also avoided delay in delivery of a replacement.

Multiple-Tier Welding

The deep-penetration properties of the electron beam make it possible to weld two or more tiers of joints simultaneously. The joints can be separated by an air space as great as several inches, provided that the space can be evacuated and the joints aligned in the path of the beam. This type of weld cannot be made by any other welding process.

In multiple-tier welding, the electron beam must pierce at least the upper tiers in such a way that the molten metal flows in behind the advancing beam as in keyholing. The molten weld metal is held in place by the combined forces of capillarity, surface tension, and viscosity. Welding conditions must be carefully selected and controlled.

Difficulties. In-line welds are progressively different in shape and size, because of the scattering and reduction in beam density and other effects on the beam that take place when it penetrates each layer of metal in turn.

Internal weld spatter may cause difficulty if it interferes with service performance and there is no access for cleaning. Other difficulties such as undercut, underfill and excessive root bead may be correctable. Hidden welds, which are difficult or impossible to inspect, require some acceptable indirect method of controlling joint reliability.

Applications. Multiple-tier welding has been applied to a variety of joints. Two-tier joints separated by as much as 3 in. have been welded in a single

pass in joining honeycomb panels to end frames or structural shapes where only one side was accessible.

The example that follows describes the problems encountered, and the methods used to solve them, in the two-tier welding of a gas-turbine component, in which two layers of 0.075-in.-thick René 41, about ½ in. apart, were welded simultaneously.

Example 481. Two-Tier Welding of René 41 Gas-Turbine Component (Fig. 31)

A unique solution to the problem of designing and fabricating a component of an aircraft gas-turbine engine was achieved by electron beam tier welding. As indicated in Fig. 31, the component consisted of a cylinder with an external flange on one end, an internal flange on the other, and a tubular annulus between. The components were assembled by welding the trough-shape ends of two subcomponent cylinders by a single two-tier circumferential weld.

The components were made of René 41, for service at elevated temperature. The chief welding objectives were to obtain sound welds and to avoid distortion of the part, and especially the alignment of the 288 holes located in the annulus less than ½ in. from the joints. (The holes had to be drilled before welding because they could not be deburred if drilled after welding.)

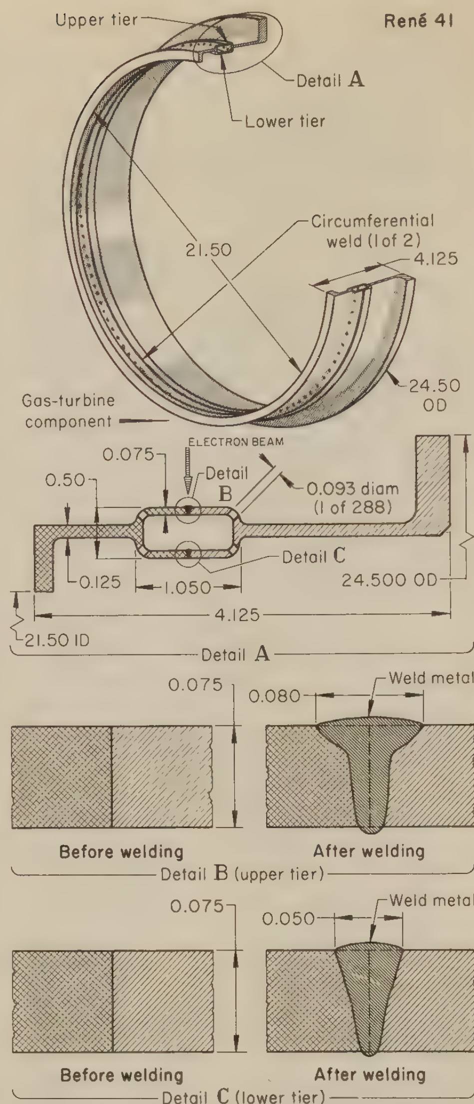
Arc welding was rejected as a possible joining method because it would have been necessary to use internal chills with gas backing in the annulus to minimize distortion and avoid atmospheric contamination. Electron beam welding not only met the basic requirements but also made both welds simultaneously, even though the two joints were separated by approximately ½ in., as shown in detail A of Fig. 31.

Fixturing was relatively simple. The joints were accurately machined square and the components were assembled between two aluminum plates fitted over the flanges. The plates were connected and forced together by bolts located inside the inner flange. This fixture was then mounted on the faceplate of a welding positioner in the vacuum chamber so that the part would rotate with its axis horizontal. The electron beam gun was in a fixed, overhead position.

Success of the two-tier welding operation depended on careful control of part alignment, beam alignment, beam focal point, power adjustment, and travel speed. The joints for the upper-tier and lower-tier welds had to rotate in the same vertical plane, although, by direct viewing, they could not be observed simultaneously. In addition, beam impingement on the joint of the lower-tier weld could be verified only by emergence of the weld bead from the underside, or by sectioning of test pieces.

Alignment of the part for true horizontal-axis rotation was done with the aid of a precision level (sensitivity of 0.0005 in. per foot) and precision spacer blocks placed on the face of the 24.50-in.-OD flange. Beam alignment was done by centering the beam spot on the reticle of the scope and moving the joint to this position. Beam focal point, beam power, and travel speed were adjusted by trial and error on test components until a satisfactory welding procedure was established. The final settings are shown in the table with Fig. 31. By adjusting the beam focus for an indicated setting midway between the two tiers, the weld shapes of Fig. 31, details B and C, were obtained.

The mushroom-head shape of the upper-tier weld was caused by the defocused condition of the beam at that point, while the somewhat oversize root reinforcement resulted from the excess of power needed to penetrate to and through the lower tier. The relatively narrower weld face of the lower-tier weld, as well as the narrowing of the weld in its progress through the joints, was explained as an effect of a charged



Joint type	Circumferential, two-tier butt
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Fixed
Maximum vacuum	10^{-5} torr
Fixtures	Bolted end plates; rotating positioner
Preheat	None
Welding power	125 kv at 9.3 ma
Welding vacuum	10^{-4} torr (min)
Working distance	12 in.
Beam focal point	Midway between tiers(a)
Welding speed (at 0.42 rpm):	
Upper tier	30 ipm
Lower tier	28.7 ipm
Beam oscillation	None
Number of passes	One, plus 30° downslope
Postweld heat treatment	Age 16 hr at 1400 F

(a) Indicated machine setting. See text of example for explanation of beam focal point.

Fig. 31. Section through a cylindrical component of an aircraft gas turbine, showing tiered welds made simultaneously by electron beam welding (Example 481)

plasma that surrounded and refocused the beam on its passage through the material. The plasma, having a net negative charge, repelled the beam electrons, causing the beam to constrict and to change its focal point. The net result on the lower tier was to produce a weld closely approaching the contour of a normal single-thickness weld made with a tight, surface-focused beam. Thus, the indicated focal-point setting was more virtual than real.

Both welds were satisfactory as to soundness and shape. Because of lack of access to the interior of the joint, weld spatter and undercutting were of concern, and spatter associated with penetration of the upper tier was a problem. Most of the particles were loosened with pipe cleaners and were flushed out with solvent at high pressure. The few small particles that remained were judged to be acceptable after radiographic examination. Undercutting was not a problem. The René 41 material was capable of withstanding considerable excess beam power, which was especially important in making the upper-tier weld.

The two-tier welding procedure was used to produce three components, which met all test requirements and were accepted.

An ingenious and practical arrangement for multiple-tier welding was used to electron beam weld more than 12,000 terminal interconnections per pumpdown, in the automated mass-production application described in the next example. The usual problems associated with the multiple-tier technique were minimized, and the joints were easily inspected.

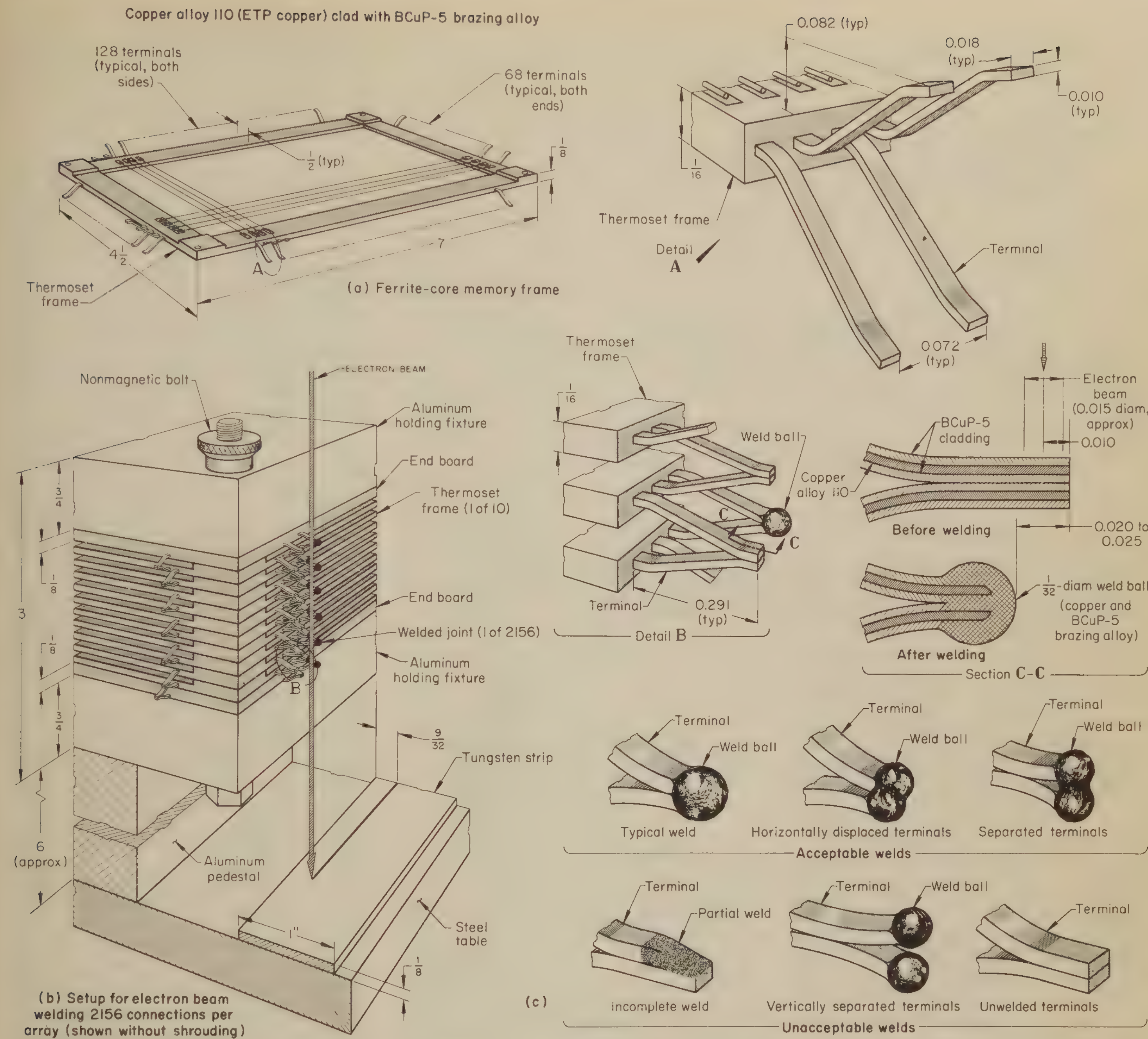
Example 482. Multiple-Tier Welding of Terminal Joints in Stacked Arrays of Ferrite-Core Memory Frames (Fig. 32)

Ferrite-core memory arrays for electronic computers were fabricated by stacking individual core frames, of the type shown in Fig. 32(a), and joining their corresponding terminals to form a network. A typical stack of frames, assembled in an electron beam welding fixture, is shown in Fig. 32(b) as consisting of ten frames (called planes) and two end boards that completed the array. This arrangement resulted in aligning the terminal leads on all four sides of the array in a series of vertical columns that alternately contained five and six terminal joints per column. Each terminal lead consisted of a 0.010-by-0.018-in. rectangular wire with a copper core and a copper-base brazing alloy cladding. Terminals were spaced on 0.036-in. centers.

Originally, terminal interconnections were made, one at a time, by resistance spot brazing, using specially designed electrodes mounted in an automatically indexed head. However, this method was not fast enough to meet the demand, and efficient mechanization was made difficult by electrode pickup and other uncontrollable process variables. Also, to ensure joint reliability, it was necessary to apply a time-consuming pull test to all joints.

When the joining operation was changed to electron beam welding, production rate was increased substantially, joint appearance and reliability were improved, and a simple visual test was found to be adequate for inspecting the welds. The electron beam procedure consisted of passing the terminal tips of a stacked array through a fixed electron beam (Fig. 32b), welding the terminal ends, column by column, on each of the four sides of the array. Six stacked arrays were welded consecutively in one chamber load. Success of the operation depended primarily on obtaining and maintaining accurate alignment of the joints with respect to each other and of the beam with respect to the terminal tips.

Three important features of the electron beam welding machine used in this operation were a long-focal-length beam, a table capable of x-y motion, and a stereoptic viewing system. Long focal length permitted the stacked arrays to be raised about 6 in. above the table to avoid the heat and spatter generated when the beam, after passing through and between the terminal columns, impinged on tungsten strips placed to absorb the energy. In addition, beam diameter remained essentially constant over the vertical depth of the array. The table accommodated six fixtured arrays and provided travel speeds of 3 to 120 in. per minute, as set by the operator. The optical system, which was collinear with the electron beam, permitted the operator to align the work accurately with the beam by means of a crosshair reticle.



Joint type	Edge flange	Machine capacity	150 kv at 40 ma	Beam oscillation	None
Weld type	Multiple tier, square groove (see figure)	Gun type	Fixed; long focal length	Welding speed	36 ipm
Fixtures	Alignment tool; holding jig; support pedestal; tungsten target plates; table with traversing carriage; optical system	Welding power	100 kv at 10 ma	Number of passes	Two
		Welding vacuum	10^{-4} torr	Welding time per pass(a)	About 0.048 sec
		Beam spot size	0.015-in. diameter	Production rate	323 connections per min(b)
		Beam focal point	Midpoint of stacked array		

(a) Time for a vertical column of terminal joints to traverse beam. (b) Six arrays (12,936 connections) welded in total time of 40 min, one pumpdown.

Fig. 32. Electron beam welding of terminals of ferrite-core memory frames used in electronic computers (Example 482)

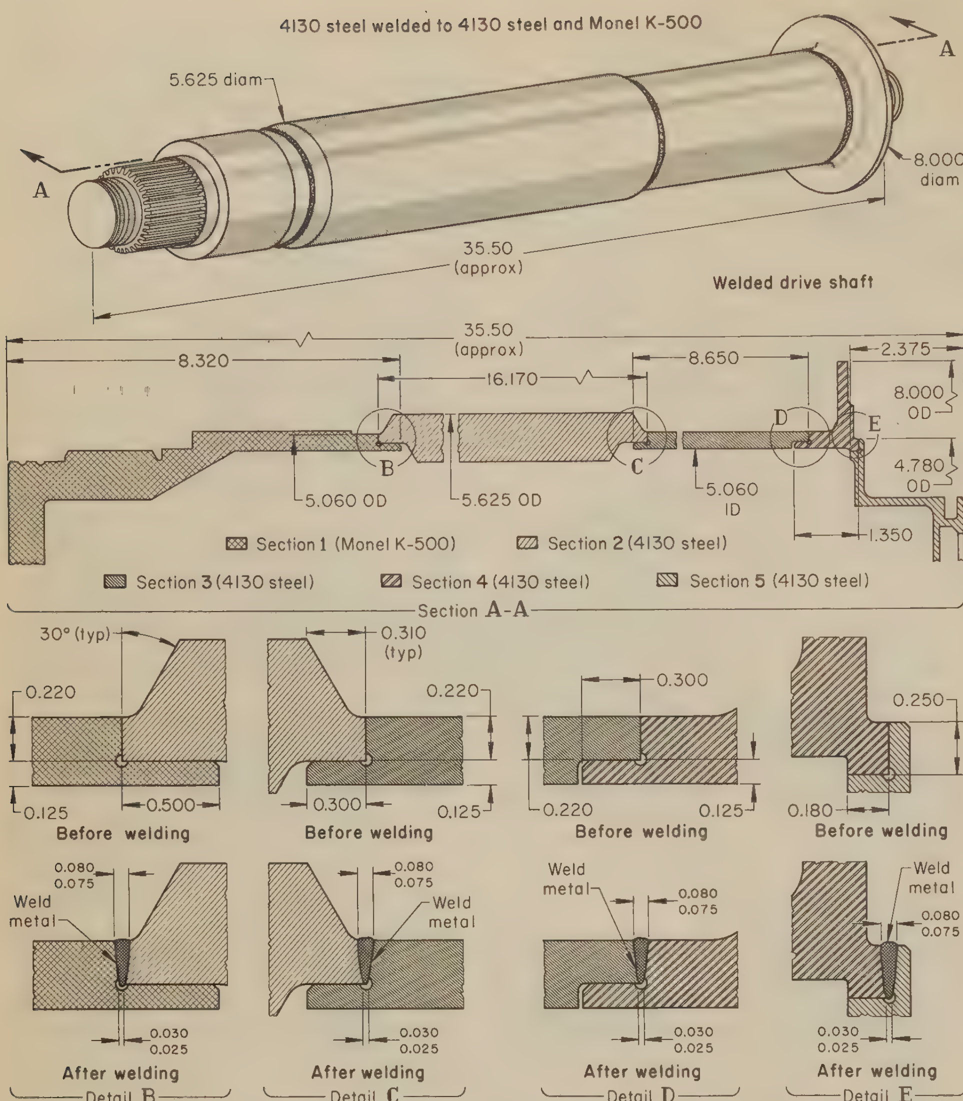
Before stacking the core frames, the upper and lower terminals on each frame were spread apart to ensure positive contact with the mating terminals of adjacent frames, as shown in details A and B in Fig. 32. The frames were then stacked in an aluminum holding fixture, to which was attached a comblike aligning tool. When the assembly was completed, the holding fixture cover was bolted in place and the aligning tool was removed. By this means, the 25,872 accurately formed and trimmed terminals in a batch of six arrays were aligned vertically within a tolerance of 0.002 in. to make 12,936 welded joints.

Fixtured arrays were next shrouded in an envelope of 0.002-to-0.003-in.-thick aluminum foil. A soft rubber roller was used to press the foil in and around the terminal joints, puncturing the foil so that the terminals were exposed for welding. This technique protected the remainder of the assembly from spatter and also grounded the electrically floating terminals, which otherwise would become statically charged by the beam to cause beam deflection.

Six 6-in.-high pedestals were secured to the table in the vacuum chamber, and the fixtured arrays were positioned accurately on the pedestals by means of locator pins. The arrays were arranged three across (x-direction) and two deep (y-direction), and were spaced about ½ in. apart at the terminal ends. All fixturing was made of aluminum or other nonmagnetic materials, to avoid magnetic beam deflection. Strips of tungsten were placed on the table around each assembly to absorb beam energy.

After pumpdown, the electron beam was focused on a tungsten target plate set at the vertical midpoint of the arrays. The beam spot, approximately 0.015 in. in diameter, was aligned on the crosshairs of the optical system, and the beam was then turned off. The terminal joints of the first array to be welded were then moved into view, with the crosshairs positioned 0.010 in. from the end of the first terminal and slightly before the starting edge.

Beam power was turned on and the table was traversed forward and back at 36 in. per minute, each column of joints passing under the beam twice. Two welding passes were made to ensure complete welding of



Joint type	Circumferential butt(a)	Welding power:	
Weld type	Square groove	0.220-in.-thick joints	115 kv at 9.6 ma
Machine capacity	6 kw at 150 kv	0.250-in.-thick joint	120 kv at 11.7 ma
Gun type	Fixed	Operating vacuum:	
Vacuum-chamber size	108 by 56 by 56 in.	Setup	2×10^{-4} torr (max)
Maximum vacuum	10^{-6} torr	Welding	5×10^{-5} torr
Fixtures	Horizontal positioner with mounting and driving plate; loading track	Welding speed	About 30 ipm
		Beam spot size	0.015 in.; flush focus
Preheat	600 F (in a furnace)	Postheat	600 F; air cool

(a) All four of the circumferential butt joints were self-backing.

Fig. 33. Five components of a hydrofoil drive shaft that were shrink fitted and electron beam welded to a tolerance of ±0.002 in. for concentricity and straightness (Example 483)

joints in the lower tiers that may have been deprived of some of the beam energy during the first pass. Ten double passes were required to make the welds on a batch of arrays. The first four double passes were in the *x*-direction, each double pass sweeping one side of three arrays per traverse. Six double passes were made in the *y*-direction, each double pass sweeping one side of two arrays per traverse. The beam was realigned for each double pass.

As each vertical column of five or six joints moved into the path of the electron beam, the ends of each terminal pair in the column were melted back 0.020 to 0.025 in., as shown in section C-C in Fig. 32, forming a shiny weld ball about 1/32 in. in diameter at each joint. The action was extremely rapid; the heating time per joint at a traverse speed of 36 in. per minute was only about 0.048 sec.

Power settings and other welding conditions were established by trial. Optimum settings for welding a ten-frame array with two end boards are given in the table accompanying Fig. 32.

One of the results of electron beam welding was to simplify quality control and inspection. Because of the approximately spherical shape of a properly made weld, it was possible to correlate joint strength with weld shape by destructive testing. As a consequence, a set of workmanship standards was set up for acceptance or rejection of the welded joints, based on visual inspection. Figure 32(c) shows the shape of acceptable and unacceptable welded joints. Visual scanning of completed arrays proved successful — none of the acceptable joints welded by the electron beam procedure described here has ever failed in a product.

A six-array batch was completed in 40 min, including 15 min for mounting the arrays and pumpdown, 15 min for electron beam setup, and 10 min for double-pass welding of the 12,936 connections. Over-all production rate was thus 323 connections per minute. Over-all rate for the original process (resistance spot brazing) had been about 51 connections per minute, including setup, alignment and handling.

Defective electron beam welds were repaired by manual resistance spot brazing, using hand-held tongs. However, the incidence of unacceptable electron beam welds was extremely low.

Welding With Extreme Accuracy

The development of feedback servomechanisms for controlling variations in beam power and beam spot size, as well as in work travel and speed, permits electron beam welding within tolerances of a few thousandths of an inch in high-vacuum machines.

With the use of closed-loop feedback control systems, variations in beam voltage and current can be held to approximately 1% for a 10% variation in the supply line, which is well within the tolerances that can be maintained by the remainder of the system.

Although the diameter of the beam spot cannot be measured directly with great accuracy, it can be estimated by measuring the width of the weld or by calibrating the controls for the focusing and beam-power settings. Depending on machine characteristics, beam spots effective for most welding purposes can be set up in the range of 0.010 to 0.030 in. in diameter without difficulty. Assuming a very small beam variation, an application requiring a beam spot of only 0.010-in. diameter would require a means of holding the joint-to-beam coincidence with a runout of less than ±0.005 in.

For welding with a 0.010-in.-diam beam, a pileup of manufacturing tolerances could easily cause the beam to miss the joint. Therefore, for most production purposes, small beam spots are not economically feasible.

Various types of travel mechanisms of rigid construction are available with runout tolerances of approximately 0.001 in. per foot or with total deviations of 0.003 to 0.005 in. for a complex traverse pattern. However, joint runout depends also on the manufacturing tolerances of the part, and accuracy of fit-up and fixturing. In some applications, 20 to 25 possible sources of error, such as magnetic deflection of the beam, and human and systematic errors in beam alignment, can be found.

Sometimes, extreme accuracy can be justified on the basis of necessity. In Example 469, 0.020-in.-wide welds were placed on 0.030-in. centers with controlled penetration. In Example 481, beam alignment was more critical than weld size in making the two-tier weld. All other factors, from part manufacture through fixturing and rotation, had to be held to close tolerances.

Examples 492 and 496 describe other applications where accuracy was a primary requirement. In the example that follows, a hydrofoil shaft was designed, for economy, in five sections to be semifinish machined, shrink fitted, and welded to very close tolerances, using a small-diameter beam.

Example 483. Electron Beam Welding of 4130 Steel and Monel K-500 Sections of a Hydrofoil Shaft (Fig. 33)

Each of the three drive shafts (Fig. 33) used on a hydrofoil watercraft consisted of five sections, which were shrink fitted and electron beam welded. Four sections were

4130 steel; the fifth was Monel K-500 (see section A-A in Fig. 33). Material and machining economy were the main reasons for sectional construction. Sections were machined from readily available tubing and bar stock. High-integrity welds were required for strength, and permissible distortion was limited to ±0.002 in. for concentricity and straightness before final machining. Each shaft was required to deliver 3600 hp at 5000 rpm, and had to balance within 0.050 ounce-inch before it could be installed.

Prior to the selection of electron beam welding, three alternative welding processes were considered. Distortion would have been excessive with gas tungsten-arc and gas metal-arc welding because of the high heat input from multiple-pass welding. Also, selection of a filler metal that would be suitable for a joint between 4130 steel and Monel K-500 would be difficult. Friction welding, which is normally suited to this type of application, gave no assurance of accurate joint alignment, and the small number of drive shafts to be produced (fewer than 12) did not justify development work on a specialized precision technique for friction welding.

The electron beam welding procedure was closely linked with the shrink-fitting operation, in that each joint was fitted and welded separately. After the first two semi-finish-machined sections (sections 1 and 2) were vapor degreased, the female section was heated to 350 F, the male section remaining at room temperature. These two sections were assembled and were held under hydraulic pressure of 3000 psi for alignment (initial interference was 0.001 to 0.002 in.). After cooling, the assembly was checked for dimensional accuracy, and then it was furnace preheated to 600 F to avoid possible weld cracking. The assembly was loaded on an outboard, track-guided positioner, pushed into the vacuum chamber, and aligned under the gun. After pump-down, the weld was made in about 45 sec, using the welding conditions given in the table with Fig. 33. A furnace postheat at 600 F was followed by visual and dimensional inspection.

This procedure was repeated for each joint, in the following order: 1 to 2, 3 to 4, 4 to 5, and 2 to 3. Before final machining, the welds were machined flush and inspected by magnetic-particle methods. After final machining, the shafts were dynamically balanced.

Use of Scanning

Scanning is a method of checking the runout between the beam spot and the joint to be welded. Its purpose is to indicate the final adjustments needed to align the beam with respect to the joint and to expose possible unsuspected discrepancies in beam behavior or workpiece travel that would interfere with welding. Details of the procedure vary with joint design and the type of equipment available; in one widely used method, a low-power beam is used for visual scanning of the joint during a simulated welding pass.

Accuracy of Beam Alignment. Beam alignment is generally a matter of workpiece alignment, as even guns of the adjustable type are usually fixed during welding. Where the gun does traverse the joint, the principles of alignment are the same. Most joints are designed for simple path shapes — straight lines and circles — that can be adequately traced with precision-made carriages, cross-feeds, turntables, eccentric tables and spindles.

General Procedure for Scanning. The workpiece is fixtured, and the joint is aligned for travel direction and is moved to its approximate location under the gun. The chamber is closed and pumped down to a vacuum sufficient for safe operation of the gun. A low-power beam is turned on and focused sharply on the workpiece surface. The specific power settings will vary with the working distance selected and the power ratings of the machine; however, they should be sufficient only to create a detectable spot without overheating the workpiece.

The joint line is then adjusted to its precise location with respect to the beam spot, the workpiece is traversed through a complete cycle, and the runout is equalized. Maximum allowable tolerance on runout is determined from a consideration of joint design and weld width, which is mainly a function of the spot size and travel speed.

Considerable latitude in required accuracy of alignment can be gained where beam oscillation can be used. Usually, if the runout approaches one-half the effective welding-beam spot width (spot size plus oscillation amplitude), the cause must be determined and corrected. If the runout is within tolerances, production parts ordinarily need only periodic scanning as a quality control measure.

Problems in Scanning. Some of the causes of excessive runout and other difficulties encountered during scanning are as follows:

1. Poor joint design; inaccurate joint preparation
2. Improper fit-up; inadequate fixturing
3. Lack of precision in workpiece traversing mechanism
4. Obstructions in the beam path
5. Indistinct or undetectable joint line
6. Beam deflection by electric or magnetic fields.

The corrections required for mechanical discrepancies are self-evident; the effects of electric and magnetic fields may be less obvious.

The negatively charged electrons that comprise the electron beam constitute a negative space charge. When the electrons strike an insulated metal part, negative charges are built up, causing mutual repulsion between the part and the beam. By grounding the part, excess electrons are conducted away. Example 482 describes the use of aluminum foil for this purpose.

To avoid unintentional deflection of the beam by nearby magnetic fields, workpieces, fixtures and tooling components made of magnetic materials should be demagnetized before welding, as described on page 521.

Scanning techniques vary in detail, depending on the type of equipment used and also on joint design. It is not always necessary to position the beam spot precisely on the joint line. When welding dissimilar metals, dissimilar thicknesses of the same metal, or certain self-locating joints, it is often necessary to position the beam a short distance from the visible joint line. A corner edge or a scribed line can often serve as a reference, or measurement can be made with an optical grid.

Some special-purpose electron beam welding machines are not intended for scanning. Nearly all general-purpose machines, however, make some provision for this operation. On machines with a fixed gun located in an upper section of the vacuum chamber, a built-in, internal, optical viewing system is generally provided for scanning. Machines having movable guns can be equipped with external telescopes and internal mirror systems.

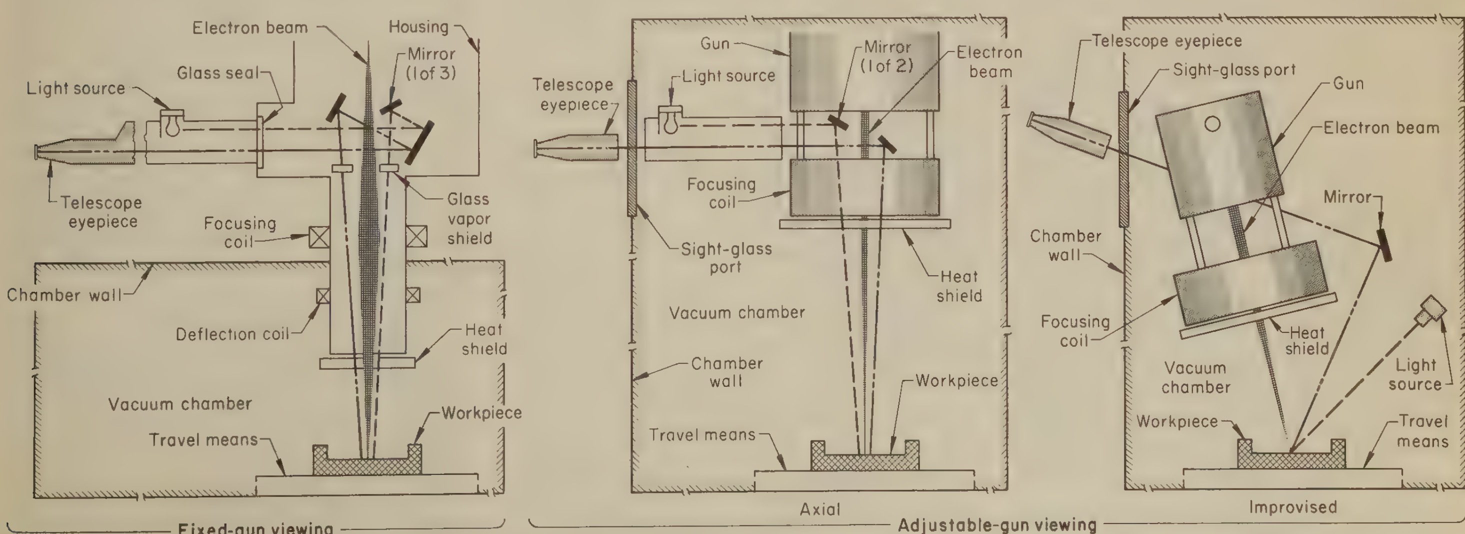
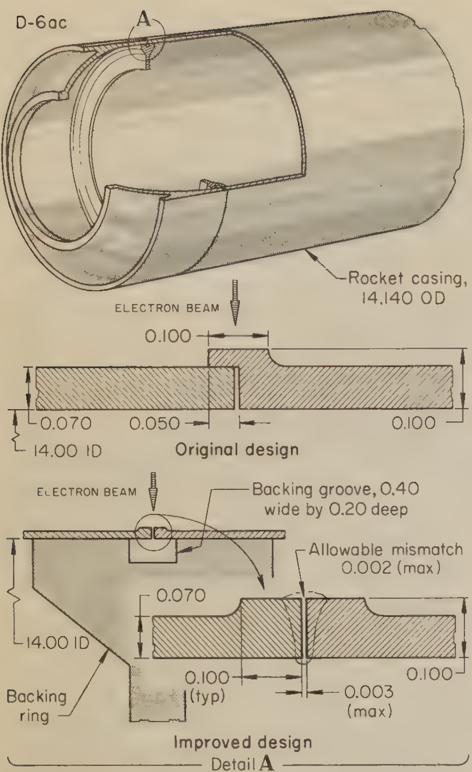


Fig. 34. Three types of viewing systems used to scan the joint for beam alignment and to observe the joint during welding



Joint type	Circumferential butt
Weld type	Square groove, integral filler-metal shoulders
Machine capacity	150 kv at 40 ma
Gun type	Fixed
Vacuum-chamber size	48 in. in diameter, 72 in. long
Maximum vacuum	10^{-5} torr
Fixtures	Holding jig; lathe-type positioner
Welding power:	
First pass	120 kv at 2 to 3 ma
Second pass	120 kv at 8 ma
Welding vacuum	10^{-4} torr
Working distance	10 in.
Beam spot size	About 0.03-in. diameter
Beam focal point	At work surface
Welding speed	44 ipm
Number of passes	Two
Pieces per load	One
Pumpdown time	8 min
Postweld heat treatment	Furnace stress relief

Fig. 35. Aft end of a rocket casing, showing original joint design and improved design that permitted optical scanning for accurate beam alignment (Example 484)

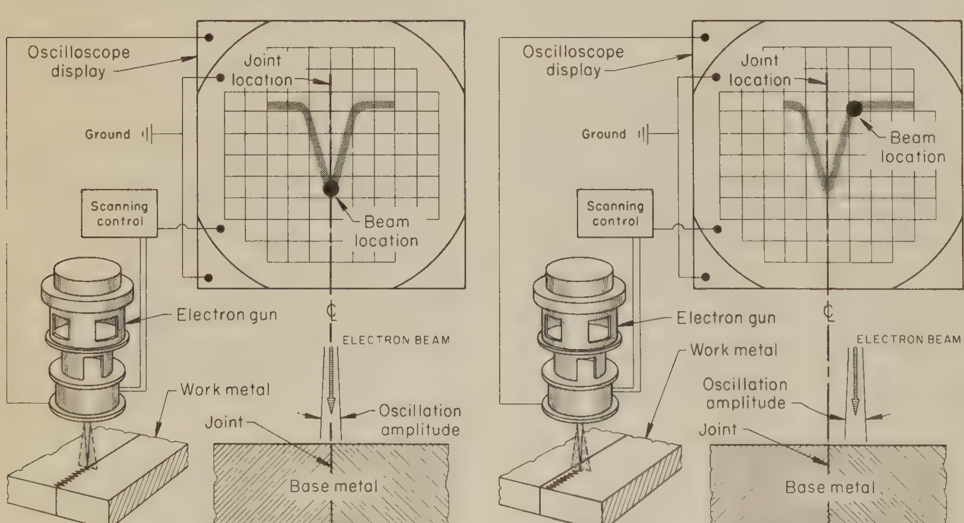
Optical Scanning. Optical systems usually consist of horizontally mounted monocular or binocular telescopes with internal illumination and reflecting mirrors that provide a line of sight coaxial with the beam path. Other viewing directions can also be improvised. Magnifying power may be 10 to 40 times, depending partly on working distance. High-precision alignment can be obtained. The optics of fixed-gun and adjustable-gun viewing systems are shown schematically in Fig. 34.

There are two common methods of using this equipment. One method makes use of a low-power beam that is sighted telescopically on the workpiece surface. Using a calibrated grid, measurements to 0.001 in. can be made. In the other method, the beam is centered on a crosshair reticle embodied in the optical system. The beam is then turned off and the workpiece joint is moved into coincidence with the crosshair, under internal illumination. The advantage of the latter method is that, after the beam is turned off, the chamber need no longer remain under vacuum, and further alignment work can be done in the open, if necessary.

On some machines, the gun chamber can be sealed off when the gun is inoperative. The method of transferring beam alignment by means of the crosshairs was used in Example 482 (low-power scanning was not needed). The full-power beam was focused on a tungsten target held at the exact focal length desired for the final operation.

Before scanning, the mirror surfaces of the internal optical system should be cleaned, because vapor deposition takes place during welding. The frequency of cleaning may vary from a few to many hours of operation, depending on the amount of vapor created and the proximity of the weld. Mirror surfaces are usually protected with glass shields that can be removed for cleaning or replacement.

A scanning operation that resulted in a change in joint design, and indicated the need for demagnetization of the workpiece, is described in the following example.



(a) Electronic scanning setup, beam on joint (b) Electronic scanning setup, beam displaced to right of joint

Fig. 36. Arrangement for electronic scanning of a joint, showing equipment, joint to be welded, and oscilloscope display (a) *with the beam centered on the joint and* (b) *with the beam displaced to the right of the joint*

Example 484. Scanning as Related to Joint Design and Effect of Residual Magnetism in Welding D-6ac Steel (Fig. 35)

A 14-in.-diam rocket casing made of D-6ac alloy steel was designed with a circumferential joint to be electron beam welded. Figure 35 shows the general location of the joint, together with a schematic representation of the internal fixture that was used to obtain accurate self-alignment and to confine spatter, rather than to provide a backing for the weld. In setting up for electron beam welding, three features of the procedure came under close review, namely: (*a*) joint design, (*b*) scanning technique, and (*c*) stray magnetic fields, which caused irregular beam deflection.

Joint Design. At first, the joint shown as the original design in Fig. 35 was considered, because its self-locating characteristics would eliminate the need for a fixture to provide close alignment of joint surfaces. This design was rejected because of difficulty in centering the beam accurately on the joint line. To permit satisfactory scanning of the joint prior to welding, and adequate visibility during the welding operation, the improved design (Fig. 35), which also provided integral filler metal to allow for final finishing, was adopted.

Scanning. In setting up the welding procedure, the last operation before welding was the scanning of the joint with a low-power, focused beam to align the joint with the beam. A small incandescent spot was generated on the fixtured, rotating workpiece, which was positioned so that the spot coincided with the visible line of the joint. This operation was performed by remote control during or after pumpdown, because gun components would deteriorate quickly if operated in air. Observation of the runout of the joint line with respect to the beam spot was made with a 16-power telescope optically arranged for viewing directly down the beam path.

Beam settings for scanning were controlled less closely than those for welding. Scanning settings used were: (*a*) beam power, 90 to 110 kv at 1.0 ma; (*b*) working distance, 10 in.; (*c*) beam focal point, sharp on work surface.

The scanning technique indicated the adjustments needed for beam alignment, and also identified areas where the beam was deflected by stray magnetic fields.

Stray Magnetic Fields. During scanning trials, erratic beam deflections were observed at several points on the casing. Although the amount of deflection was small at the low beam power of scanning, it would increase considerably under full welding power. It was found that the steel casing components had been magnetic-particle inspected after machining, and had retained some of the induced magnetism.

Demagnetization was made a standard procedure for all casing components. This was done by removing the parts slowly from within the magnetizing coil of the magnetic-particle testing machine after testing was completed. The parts were then degreased and checked for residual magnetism with a magnetic-field indicator. Just prior to welding, when it was already in the welding chamber, the assembly was again checked (in the same way) for magnetic fields. The steel fixturing used was demagnetized at the outset of the production run, and, although periodically checked, did not require further demagnetization in the run. After all corrections were made, final runout during rotation was estimated to be within ±0.006 in. max.

Having established the proper conditions for welding, a trial run was made to determine the actual settings for production welding. The weld was made in two passes by rotating the casing under a fixed beam centered vertically on the joint. The first pass was made at low power to hold the parts firmly in place for the second, or penetrating, pass. No cosmetic pass was made, because the weld was later to be machined flush. Neither preheat nor any special beam oscillation technique was used. At the completion of welding, current

was downsloped over an additional 5° of revolution. Machine settings and other welding conditions are summarized in the table accompanying Fig. 35.

After welding, casings were furnace stress relieved. The joint was machined and the entire casing was grit blasted. Before applying a final hydrostatic test, the joints were completely examined by x-ray and magnetic-particle inspection.

Scanning Without Optics. Scanning can also be done without visual aids where great precision is not required. On machines that are not equipped with viewing optics, scanning is done by direct observation through sight-glass ports. From one to four such ports may be located in the chamber wall, usually spaced 90° apart, to permit checking beam alignment from several angles. The beam spot is generated the same as for optical scanning.

Electronic Scanning. Checking the location of an electron beam with respect to the joint can be done with an electronic device that displays the relationship on an oscilloscope. The equipment makes use of a low-power electron beam that is made to oscillate at 60 hertz transversely across the joint. The amplitude of the oscillation is sufficient to display the workpiece surface for a short distance on either side of the joint, as well as the joint line itself. In addition, each oscillation pulse is interrupted momentarily to permit the beam to assume its normal welding position, causing a relatively large spot to appear on the display. When the spot coincides with the joint line of the display, the beam is accurately aligned for welding.

Figure 36(a) shows the display condition for a beam centered exactly on the joint. The V represents the joint line, with the beam spot centered accurately; the two horizontal arms (of equal length with a centered beam) at the top of the V represent the adjacent workpiece surface. The broken lines above the work (at left in Fig. 36a) show the plane of oscillation; the wavy line along the joint in the same view shows the approximate amplitude of oscillation.

If the beam location were displaced to the right of the joint, the display would look like Fig. 36(b); an opposite-handed display would indicate displacement to the left. By the relative depth of the V, the display also indicates the amount of joint separation from apparent zero to approximately 0.006 in. A joint mismatch of a few thousandths inch is indicated by the relative height of the horizontal arms.

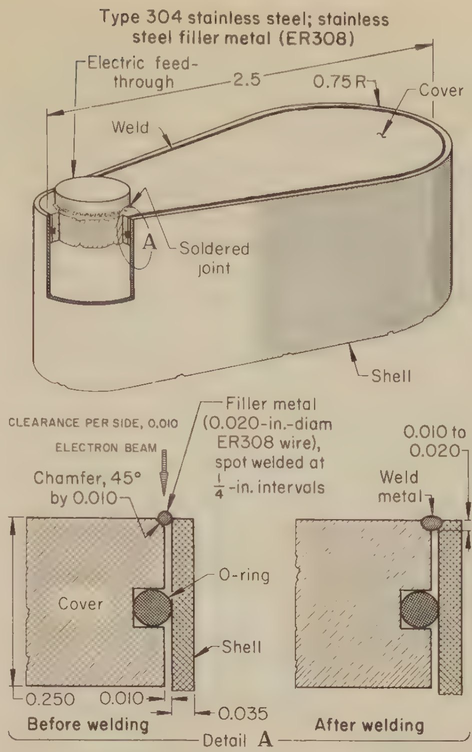
In setting up for electronic scanning (under vacuum), the work is provisionally aligned as for optical scanning, making sure that the joint line is parallel to the direction of travel.

Joint Tracking

Joints that have a path that deviates from a straight line or circle usually require an automatic tracking device for electron beam welding of production quantities. For small production lots, manual tracking, using a coordinate drive having separate controls, sometimes can be used. Whether the method is controlled manually or automatically, the motion required to generate the curve is usually imparted to the workpiece, although limited motion can be imparted to some guns.

Manual Joint Tracking. In manual tracking, the welding operator must closely observe the joint at the point where the weld is being made, to anticipate any change in direction. The conditions best suited to this type of operation are: (*a*) a joint path consisting of a smooth curve, (*b*) slow travel speed, and (*c*) a low-power beam with oscillation, to form as wide a weld as possible. The welding operator is capable of regulating two motions of the workpiece (or gun) by manually adjusting the remote controls of the travel mechanism.

For a low heat input, to permit the use of the low welding speeds needed when manual tracking is used, beam pulsation can be combined with beam oscillation, as described in the following example.



Joint type	Irregular, circumferential edge
Weld type	Seal, with preplaced filler metal
Machine capacity	120 kv at 25 ma
Gun type	Triode; fixed; with tungsten hairpin filament
Vacuum-chamber size	23 by 36 by 36 in.
Maximum vacuum	10^{-6} torr
Fixtures	Copper chill; rotating positioner; horizontal table with x-y motion
Filler metal	0.020-in.-diam ER308
Working distance	6 in.
Beam focal point	Sharp at work surface
Welding power	100 kv at 3.5 ma
Welding vacuum	10^{-4} torr
Beam pulsation	100 hertz, 2-millisecond pulse length
Beam oscillation	Circular, 60 hertz, 0.029-in. amplitude
Joint tracking	Manual
Tracking speed	2 to 3 ipm

Fig. 37. Top portion of a reusable electronic enclosure showing the seal weld that was made with a pulsed and oscillated beam, allowing the use of low welding speed for manual joint tracking. The small weld and thick cover plate permitted the seal to be machined off and rewelded. (Example 485)

Example 485. Use of a Pulsed Beam To Permit Low-Speed Manual Joint Tracking in Making a Seal Weld Designed for Removal and Rewelding (Fig. 37)

The problem of sealing an electronic enclosure designed for repeated reuse was solved by developing a manual, pulsed electron beam welding technique. The portion of the device involved in the sealing operation is shown in Fig. 37 as consisting of a 0.035-in.-thick shell and an irregularly shaped, 2.5-by-1.5-by-0.250-in. cover plate, both of type 304 stainless steel.

Designing for reusability resulted in three special features of the joint. The cover plate was made thick to permit machining off and rewelding the seal many times during the life of the device. To obtain adequate sealing with the least loss of material and time in machining, weld penetration was specified as 0.010 to 0.020 in. A joint clearance of 0.010 in. between the cover plate and shell was provided for easy removal of the cover, but this clearance made it necessary to use a preplaced filler-metal wire, as shown in detail A of Fig. 37.

Other special aspects of part design determined details of the welding procedure. An O-ring seal was placed in the joint to prevent metal vapors generated during welding from contaminating the internal mechanism. The soldered joint of an electric feed-through passed close to the weld joint, requiring low heat input in welding. The oval configuration of the joint made manual joint tracking necessary — the few parts required made it impractical to construct an automatic tracking tool. Adding to the difficulty in tracking was an internal magnet, which caused beam deflection.

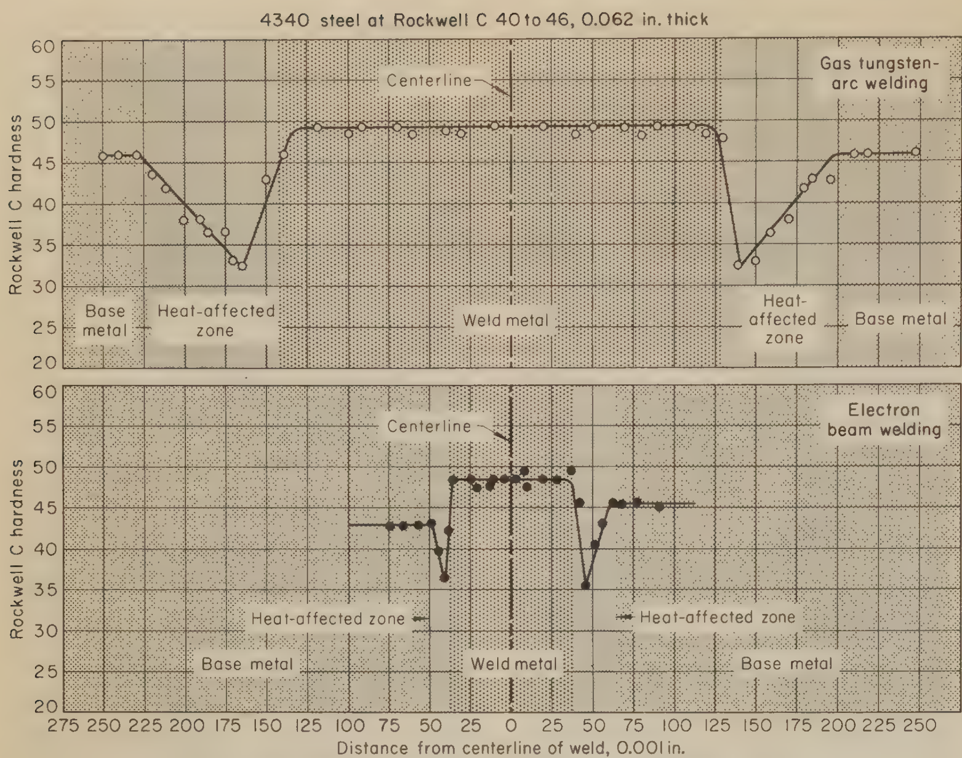
To obtain low heat input, a heavy copper chill (not shown) was built to encase the shell. To reduce the speed of welding to a level enabling the welding operator to track the joint, the electron beam was energized in pulses and was circularly oscillated, while the gun remained in a fixed vertical position.

Before welding, the joint was wiped clean with a solvent, the components were assembled, and chill blocks were attached. Filler-metal wire was placed in the beveled groove of the joint and was capacitor-discharge spot-weld tacked at ¼-in. intervals. The assembly was then mounted on a positioner to rotate about a vertical line that intersected the midpoint of the axis of symmetry of the cover plate. The rotating positioner, in turn, was mounted on a horizontal table (in the vacuum chamber) equipped with x-y motion control. Both rotation and horizontal x-y motion could be independently controlled by the operator. However, in welding, only rotation and horizontal y-motion (toward and away from the operator) were used. Observation of the joint was made by telescope.

After pumpdown and beam alignment, the part was rotated to produce tangential speeds of about 2 to 3 in. per minute while the part was moved back and forth to hold the beam on the joint. Welding was accomplished in one pass, using the machine settings and other welding conditions given in the table accompanying Fig. 37.

Automatic Joint Tracking. Mechanical, electromechanical, numerical-control, and computerized systems are sometimes used for welding joints that deviate from straight lines or circles.

Devices that track the joint by using a stylus or follower wheel as a probe are limited in their applicability to electron beam welding. The probe provides transverse motion as the workpiece rotates or travels longitudinally. This type of probe requires a groove in or parallel to the joint, or an edge that duplicates the joint contour. For tightly fitting, flush butt joints, a groove may be cut along the joint. Natural tracking surfaces can be provided by edge, lap, T and corner joints.



Rockwell C hardness was obtained by converting microhardness readings taken on cross sections of the welded joints at their midpoints after stress relief at 650 F.

Fig. 38. Hardness traverses across electron beam (high-vacuum) and gas tungsten-arc welded butt joints in 0.062-in.-thick quenched-and-tempered 4340 steel

If the probe rides in the joint, it must precede the beam, to avoid heat damage and spatter; its response to a change in direction is therefore early with respect to the response of the beam spot. Probes that ride an edge or surface that duplicates the curve of the joint can often be placed abreast of the beam spot. However, the minimum radius that can be translated depends on the diameter of the stylus or wheel. Probes can induce translation mechanically or electromechanically.

Mechanical Joint Tracking. The limitations of the mechanical probe can sometimes be overcome by using the workpiece itself as a follower. For instance, in Example 485, the positioner spindle could have been spring-loaded so as to cause the workpiece shell to bear against a fixed roller. The moving joint would remain in constant relation to a fixed beam at the point of contact with the roller, and there would be no delay in response time. Welding speed could be controlled by varying the rotational speed of the spindle.

The use of a template to obtain transverse motion by pantograph or equivalent linkage introduces several undesirable variables, namely: (*a*) the above-mentioned limitation on follower diameter, (*b*) loss of precision because of play in the linkage, (*c*) delay in response time for the same reason, and (*d*) the problem of superimposing the generated motion on a pre-existing path. Either the workpiece table or the gun would have to float freely in the transverse direction. Another consideration is the space occupied by the equipment in relation to the size of the vacuum chamber.

Electromechanical joint tracking systems make use of a probe equipped with left-hand and right-hand transducers that create an electrical signal when the probe is displaced in these (transverse) directions. The signal is relayed to servomotors, which operate to move either the gun or the workpiece table in the direction that will reduce the signal to null. Because these probes track in the groove or along an edge of the joint, the signal can be early, but there is no problem as to superimposing independent paths. Precision is usually better, response-delay time is shorter, and other problems associated with mechanical tracking with templates are avoided.

Tape-Controlled Joint Tracking. Workpiece (or gun) motion can be programed for the complete welding cycle by conventional numerical-control equipment. The actual position of the workpiece with respect to the programed tape input can be controlled to approximately ±0.001 in. As with other tracking systems in which the generated motion is independent of the joint path, the two paths must coincide. There must be a high degree of assurance that the prior processing of the workpiece, its fixturing, and beam alignment have been done with repeatable accuracy. The tape input information must be sufficiently fine to generate the curve with the desired accuracy.

Computerized joint tracking can be used in a manner that is analogous to numerical control.

Beam Oscillation

On machines equipped with deflection coils, oscillation (as well as static deflection) can be imparted to the beam by a separate control circuit. Beam oscillation is used to perform a number of useful functions. Oscillatory motion is usually circular or rectilinear (straight-line), the latter being either transverse or longitudinal with respect to joints aligned on the x-axis or y-axis. Amplitudes (full sweep) of ¼ in. or more are possible, but those commonly used range from 0.010 to 0.125 in., with frequencies from 35 to 1000 hertz.

Beam oscillation is used to produce wider welds, slower cooling rates, and more uniform weld shape, without necessarily defocusing the beam. Accuracy in beam alignment and joint tracking is less critical.

Welds somewhat wider than normal are required in joints that have relatively large root openings, or that make use of filler-metal preplacements, as in Examples 475, 485, 493 and 494 in this article. Oscillation was used in these applications and in bridging the three-member joints in Example 469.

Lower cooling rates that result from larger welds permit more outgassing from materials containing impurities, and thus help to control porosity. Welds made in metals subject to embrittlement during or after fast cooling can benefit from beam oscillation and defocusing, as described in Example 503.

One of the more useful effects of oscillated beams, as compared to stationary beams, is the general improvement of weld shape. Oscillation with or without defocusing has been used to avoid excessive undercut and underfill, as described in Examples 477, 491 and 495.

Uneven penetration in partial-penetration welds is undesirable and sometimes intolerable because of the possibility of melt-through. Beam oscillation in Examples 492 and 503 helped to reduce variability in penetration depth at the root of the weld. The added assurance of better process control was sufficient reason for using oscillation in Example 496.

Beam oscillation is not always used, even though available. Except for penetration control, most advantages can usually be duplicated by using defocused beams. Also, the wider weld and greater heat input may be a disadvantage, as in welding thin foils.

Use of a Pulsed Beam

Beam operation can be changed from continuous to intermittent on machines equipped with pulsing controls. Although available repetition rates (frequencies) and pulse lengths depend on the control unit, frequencies in the range of 0.1 to 3000 hertz with pulses up to about 60 or 70 milliseconds in duration are representative. Beam pulsation reduces the rate of heat input, but is independent of other beam conditions. Therefore, pulsation can be combined with oscillation and deflection, as well as travel speed, to influence weld behavior (see Example 483).

At very low frequencies, such as 1 hertz, with a 5 to 10 millisecond pulse length, each pulse produces a separate weld, even at low travel speed. By increasing travel speed and adjusting pulse frequency and pulse length, tack welds, spot welds, or intermittent welds can be made at normal production rates. Increasing pulse frequency to approximately 35 to 100 hertz while

maintaining short pulse lengths makes it possible to overlap the successive welds to form a continuous weld at speeds suitable for manual tracking.

Pulsed beams generally result in lower peak temperatures, especially in the area adjacent to the weld, as compared to continuous welding, although total heat input may be greater because of the slower welding speed used. At higher pulse frequencies, pulsation has been used to control the solidification pattern of the weld and the microstructure of the heat-affected zone. Pulsation also has been used in rewelding to fuse cold shuts, fill gas pockets, and smooth irregular root areas.

Repair and Planned Salvage

Electron beam welding is used to make welds for repair or planned salvage that would be impossible or excessively slow and costly by any other method. The application of electron beam welding to repair applications is found in Examples 479, 480, 488 and 494, and mentioned in Example 476.

Weld joints that were designed for planned salvage are described in Examples 485 and 489.

Electron Beam Brazing

Electron beam welding equipment and techniques have been used to a limited extent for brazing. The high vacuum used in the work chamber (10^{-4} to 10^{-5} torr) permits adequate flow of the brazing filler metal in properly cleaned joints without using reducing atmospheres or fluxes (see Example 631 in the article on Brazing of Stainless Steel).

Welding of Low-Carbon Steel

Low-carbon steels are readily electron beam welded. Grain size in both the weld and the heat-affected zone is significantly smaller than in arc welds, because of the lower heat input and extremely rapid heating and cooling.

Rimmed steel causes excessive gassing. A technique used to weld rimmed steel is to sandwich an aluminum alloy shim about 0.010 in. thick in the joint to provide deoxidizing action during welding, as described in the subsection on Preventing Porosity, page 539. Welding at a low travel speed or otherwise adjusting welding conditions to produce a more tapered weld and thus to allow more time for the escape of gases from the molten weld metal also helps to reduce porosity.

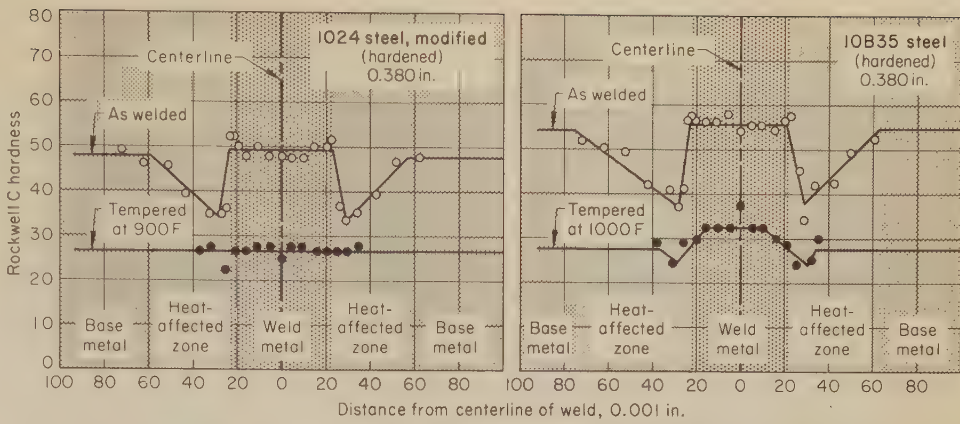
Semikilled steel is easier to weld than rimmed steel, but some oxygen may remain to cause porosity. Fully killed steel is readily weldable.

Applications. Aluminum-killed 1017 steel 0.070 in. thick was butt welded by the nonvacuum electron beam process in mass production in Example 467.

Low-carbon steel was electron beam welded to other base metals in Examples 470 and 498.

Welding of Hardenable Steel

The variation in weldability by the electron beam process among hardenable steels follows the same pattern as for



Rockwell C hardness was obtained by converting microhardness readings taken on cross sections of the welded joints at their midpoints.

Fig. 39. Hardness traverses across electron beam (high-vacuum) welded butt joints in 0.380-in.-thick heat treated 1024 (modified) and 10B35 steel, as welded and as tempered

arc welding these steels. Properties of electron beam welds in a given hardenable steel differ from those of arc welds mainly because of the narrowness of the fusion and heat-affected zones and the extremely rapid heat-melt-cool cycles.

Hardness traverses across the midpoint of electron beam (high-vacuum) and gas tungsten-arc welds in 0.062-in.-thick heat treated 4340 steel are plotted in Fig. 38. For both welds, maximum hardness was produced uniformly in the weld metal, and hardness dropped off abruptly at the edge of the weld metal.

Similar hardness traverses for electron beam welds in 0.380-in.-thick heat treated 1024 (modified) and 10B35 steel are shown in Fig. 39. The hardness profile across these two welds was similar to that for the electron beam welds in 0.062-in.-thick 4340 steel. Tempering after welding eliminated or minimized the hardness differential in the heat-affected zone (Fig. 39).

Prevention of Cracking. Cracking can be a problem in electron beam welding of hardenable steel, just as in arc welding, if the weld is made in a highly restrained joint, especially in welding parts that have been hardened. Deep circular welds in heavy sections are particularly troublesome. Partial-penetration welds are more likely to crack under restraint than full-penetration welds. It is desirable to place the joint in a location that will allow the part to shrink freely as it cools after welding.

Welding through carburized or nitrided cases is not recommended.

Cracking of electron beam welds in hardenable steel can also be minimized by: reducing the welding speed to allow more buildup of heat in the base metal; preheating; postheating; and allowing the work to cool in the chamber after welding, for slower cooling.

Medium-carbon steels, except for the free-machining types, are readily electron beam welded (for hardness traverses, see Fig. 39). Weldability decreases with increasing carbon content.

Example 470 describes the electron beam welding of hardened 1042 (at Rockwell C 57) to 1019 steel. In Example 468, Hastelloy W filler metal was used to prevent cracking.

Low-alloy steels containing less than 0.30% carbon are usually electron beam welded without preheating or postheating. When preheating is used, as to prevent cracking in highly restrained joints, a temperature of 500 to 600 F is usually adequate. If the part has been hardened and tempered prior to welding, the postweld tempering must be done at a temperature slightly below that at which the base metal was originally tempered.

Two of the most frequently electron beam welded alloy steels of this type are 8620 and 9310. Components made of these steels often are case hardened, then are assembled by electron beam welding, without distortion or heat damage to the case. Before welding, the case should be removed from the immediate vicinity of the joint, to avoid microcracking of the case.

In Example 465, a case-hardened 8620 steel shaft was assembled with a 0.180-in.-deep circumferential weld to a heat-resisting alloy casting, to make a supercharger impeller. Examples 504 and 505 describe the electron beam welding of case-hardened 9310 steel.

High-strength alloy steels containing more than 0.30% carbon are electron beam welded either in the annealed or the normalized condition or in the quenched and tempered condition, although weldability is better for the annealed or normalized condition. The hardness profile for electron beam welds in hardened high-strength alloy steel sections no thicker than about ¼ in. is ordinarily like that shown for 0.062-in.-thick heat treated 4340 steel in Fig. 38, and joint strength can approach that of the base metal, without preheating or postweld treatment other than stress relief.

In electron beam welding thicker sections of high-strength alloy steels, preheating or postheating, or both, is usually needed to prevent cracking. In studies on full-penetration, single-pass welding of 0.6-in.-thick annealed D-6ac steel, cracking was observed when preheating was not used, and was eliminated by preheating at 1000 to 1050 F. Welding was started with the joint at a temperature of 700 F, and the joint temperature remained above 650 F for 8 to 10 min after completion of the weld. Hardness profiles for the joints welded with and without preheat are shown in Fig. 40. Sound welds were also obtained in 2.2-in.-thick annealed

D-6ac steel, after preheating to 800 to 850 F, starting welding when joint temperature was no lower than 500 F.

In the example that follows, hardened D-6ac steel 0.030 in. thick was welded without preheating; the weldment was tempered at 1000 F.

Example 486. Welding of Hardened D-6ac Alloy Steel With Average Joint Efficiency of 95% (Fig. 41)

In making missile cases 8 in. in diameter by 48 in. long from D-6ac steel, hardened-and-machined head closures were joined to 0.030-in.-thick shell cases that had been ausform-strengthened by power spinning. Welding was done without preheat and, as shown in Fig. 41, the beveled edges provided a self-aligning joint, requiring only end-thrust tooling during welding.

The table with Fig. 41 lists the principal welding conditions, and section A-A shows the extent of fusion obtained. The weld reinforcements resulted from upsetting of the restrained base metal. Welding was done in three penetration passes and one cosmetic pass; no filler metal was used.

Postweld heat treatment consisted of tempering at 1000 F. Tests on transverse joint specimens showed an average tensile strength of 249,000 psi, with an average joint efficiency of 95%.

A total of ten cases was produced.

Electron beam welding was selected in preference to arc welding, for the following reasons (see also Example 500):

1 Base-metal properties were not decreased significantly in welding.
2 Preheating was unnecessary.
3 Rigid backup tooling was not required.
4 Finish-machined components were welded without excessive distortion.
5 Self-aligning joints simplified fixturing.

Applications similar to Example 486 are described in Example 500, in which a cost comparison is given for electron beam welding vs gas tungsten-arc welding, and Example 484, in which the work-metal thickness was 0.100 in. Other applications involving high-strength alloy steel are described in Examples 464, 471, 483 and 503.

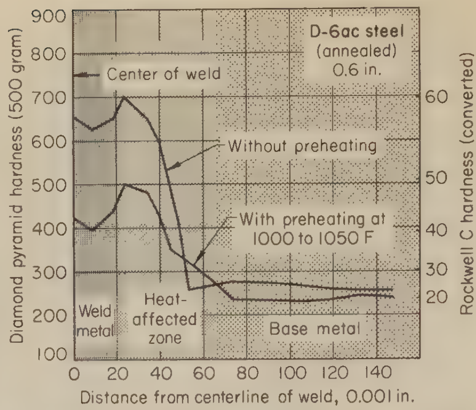
High-Carbon Steels. Because of the low total heat input and the rapid thermal cycling that are characteristic of electron beam welding, weld cracking of steels containing more than 0.50% carbon is less likely than in arc welding. Even high-carbon alloy steels such as 52100, which are seldom arc welded, have been electron beam welded on a high-production basis, with more than 400,000 welds made annually on some parts. The 52100 steel is welded in the spheroidize-annealed condition in applications where joint performance is not critical to the function of the part, and service stresses in the joint are low. Preheating and postheating are necessary.

In the example that follows, initial difficulties were encountered in electron beam welding a simple circular joint in 52100 steel to a depth of 0.145 in.

Example 487. Change in Joint Design and Use of Slow Cooling To Prevent Cracking of Welds in Medium-Vacuum Welding of 52100 Steel (Fig. 42)

Attempts to weld two bolting lugs of 52100 steel to an aircraft control housing of the same material resulted in cracking. The weld joints were located in an area that would be lightly stressed in service. The material was procured and welded in the spheroidize-annealed condition, and the part was hardened after welding.

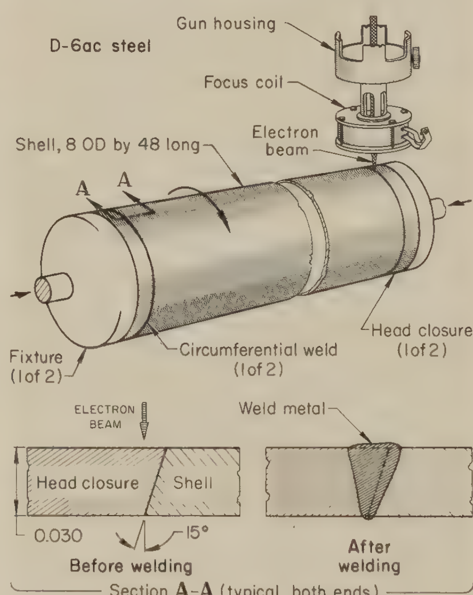
The original design, which required welding the two lugs to the shell along approximately 90° arcs of contact, is shown at the left center in Fig. 42. Carefully machined and cleaned parts were assembled in a fixture similar to the one shown at the top in Fig. 42, to maintain a nominal joint clearance of 0.0005 in. The joints were electron beam welded, without preheating, in a single pass by rotation under a beam with a fixed operating position.



Hardness traverse across midpoint of electron beam (high-vacuum) welded butt joint in 0.6-in.-thick annealed D-6ac steel, as-welded, with no preheat and with preheat at 1000 to 1050 F

Fig. 40. Effect of preheating on hardness

When cracking resulted, a new design and procedure were developed, to reduce and balance shrinkage stresses and to obtain a lower cooling rate. The lugs were replaced by a circular ring (Fig. 42, right center, and detail A). Because of its symmetrical shape, the ring was judged to be less susceptible to cracking than the lugs had been. Instead of a joint clearance, an interference fit of 0.0006 in. max was specified, to reduce residual shrinkage stress. In addition, a preheating, welding and postheating procedure was adopted that retarded cooling after welding.



Joint type	Circumferential butt
Weld type	Slant groove
Machine capacity	30 kv at 500 ma
Gun type	Pierce; fixed
Welding power	20 kv at 25 ma
Welding vacuum	5×10^{-5} torr
Welding speed	39 ipm
Fixture	Lathe-type positioner
Preheat	None
Postheat	Tempered at 1000 F

Fig. 41. Missile case and lower portion of electron gun column as set up for welding in a vacuum chamber (Example 486)

Before assembly, the joint surfaces were ground for dimensional accuracy. Cleaning was done by one dip and two sonic immersions in solvent. Where necessary, the joint surface of the ring was polished with fine abrasive. The interference fit was made by heating the ring to 350 F and pressing it in place before the entire assembly was preheated. The assembled fixture was fitted on a turntable for rotation. Beam alignment and settings were made in the conventional manner. Details of the machine settings and other welding conditions are summarized in the table with Fig. 42.

Preheating consisted of heating the assembly to 350 F before fixturing. To lengthen the heat cycle during welding, a short current upslope was used, and full welding power was applied for two passes (revolutions). Power was then downsloped to zero for $1\frac{1}{4}$ revolutions, making a total of $3\frac{1}{4}$ revolutions for the complete welding cycle. The lengthened heat input provided uniform joint temperature, and the downslope retarded cooling in the weld area. One part was welded per chamber load; within minutes after the chamber was opened, the part was placed in a furnace for stress relieving at 1200 F for 1 hr.

As shown in detail A of Fig. 42, joint penetration exceeded the thickness of the ring flange. To ensure full penetration of the 0.090-in. thickness of the ring on the finished assembly (after machining), and to avoid possible root porosity at the level of the finished ring, the weld was made to exceed the 0.145-in. minimum depth.

The preheating and postheating passes, plus the improved design and the interference fits, were credited with eliminating the cracking that had previously occurred immediately after welding. Postheating reduced the hardness of the weld to about Rockwell C 40. Without heat control, weld hardness had reached Rockwell C 57. After machining, the housings were hardened, finish machined, and ultrasonically inspected. No cracks were permitted.

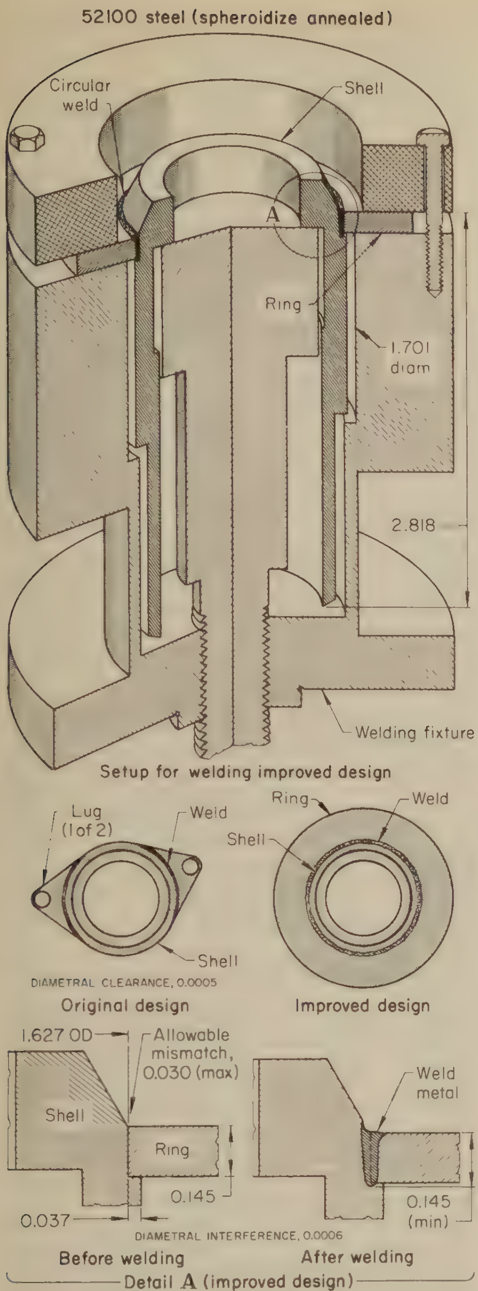
Welding of Tool Steel

The chief advantage of electron beam welding over other welding processes in joining tool steels is its ability to produce joints at high speed without annealing or other heat treating operations. Hardness profiles similar to those shown for low-alloy steels in Fig. 38 and 39 were also obtained for H11 tool steel. For full-penetration butt welds on hardened (Rockwell C 50) sections 0.225 in. thick, the hardness of the weld metal and the immediately adjacent base metal was Rockwell C 56 to 57, and hardness dropped to a minimum of Rockwell C 43 to 46 in the heat-affected zone, as measured after double tempering at 1025 F. The overtempered portion of the heat-affected zone was only 0.005 in. wide.

Small dies of D2 tool steel have been electron beam welded in production. A larger operation is the production of bimetal band saws. Specially designed medium-vacuum machines are used to produce band-saw blades by welding $\frac{1}{16}$-in.-wide M2 high speed steel cutting-edge strips to 6150 steel bands. The composite blade is about $\frac{1}{32}$ in. thick and is welded at speeds above 200 ipm in a special vacuum chamber.

In an unusual application, described in Example 471, $\frac{5}{16}$-in.-thick duplex armor plate made of equal thicknesses of H11 tool steel and high-strength alloy steel AMS 6545 was welded without preheating or postheating.

The example that follows describes a salvage application in which both preheating and postheating were used.



Joint type	Circular corner, self-backing
Weld type	Square groove
Machine capacity	60 kv at 250 ma
Gun type	Pierce; triode(a)
Filament	Tantalum
Vacuum-chamber size	18 by 18 by 22 in.
Maximum vacuum	1.5 × 10⁻² torr
Fixtures	Holding jig; turntable
Preheat	350 F for ½ hr
Welding power	59 kv at 48 ma
Welding vacuum	6 × 10⁻² torr
Pumpdown time	30 to 45 sec
Beam spot size	About 0.030-in. diameter
Beam focal point	At surface
Power density	4 megawatts per square inch
Welding speed	53 ipm (10.4 rpm)
Revolutions per weld	3¼(b)
Total travel time	18.7 sec
Production rate	10 pieces per hour(c)
Postheat	Stress relieved at 1200 F for 1 hr

(a) Fixed operating position; vertically adjustable up to 19 in. (b) Cycle consisted of two revolutions at welding power and 1¼ revolutions on current downslope. (c) Does not include 3 hr for equipment setup and dismantling.

Fig. 42. Housing for an aircraft accessory control, showing original unbalanced flange design, which was likely to crack, and the improved ring-flange design, welding fixture, and improved joint design for medium-vacuum welding (Example 487)

Example 488. Salvage of a Damaged Tool Steel Die by Welding On a Replacement Flange (Fig. 43)

Electron beam welding was used to salvage a metal-powder compacting die made of H11 tool steel, the flange of which was damaged beyond use. The inside diameter of the die stem had been finished to a critical dimension, at considerable expense, making salvage desirable. The principal cost factor, however, was that a high-production compacting press was idle for the want of a die.

Figure 43 (top view) shows a cross section through the die, with the damaged flange machined off and a new flange press fitted and welded in place. The hardness of the H11 die was Rockwell C 60, and the new flange was of the same tool steel at the same hardness.

Salvage procedure consisted of the following operations:

1. Both parts were machined to dimensions (see Fig. 43) with a 0.002-in. diametral interference at the stem neck, and they were solvent cleaned. To reduce downtime, the joint on the stem was ground to dimensions at the same time that the flange was being machined, hardened and ground.
2. Press fitting was accomplished by heating the flange to 500 F (the stem being held at room temperature), and fitting the parts together on an arbor press. Flange and stem were mechanically held in position during cooling. Maximum surface mismatch allowed at the joint was 0.010 in.
3. The assembly was furnace preheated to 500 F (2 hr at temperature), and clamped in a three-jaw chuck that was mounted on a positioner in the vacuum chamber.
4. Welding vacuum was attained while the joint was positioned for precise beam location for making weld No. 1 (circumferential), in the horizontal-rolled pipe position.
5. The power settings, beam focus and welding speed were determined by trial before the repair operation was attempted (see table with Fig. 43). Because of the uncertain consequences of having the two welds intersect, they were kept at least 0.030 in. apart. Macrosections of welds on testing stock were examined to verify the settings.
6. After weld No. 1 was completed, the part was removed from the vacuum chamber and transferred to a furnace; it was heated to 500 F, held for 2 hr, and furnace cooled.
7. The weld was then examined visually and by magnetic-particle inspection.
8. Weld No. 2 (circular) was completed by the same procedure, except rotation was about the vertical axis and power settings were different (see table with Fig. 43).
9. The face and outside diameter of the flange were ground. No change in size or hardness of the internal die surface occurred during welding.

Salvage by electron beam welding saved an estimated $200 in die cost and about two days of downtime, as compared with making a new die. Other welding methods were considered impractical because (*a*) the heat input would have decreased the hardness of the die and possibly the dimensions of the bore, and (*b*) annealing and reheat treatment would have been necessary, with the consequent danger of further distortion.

The procedure was used to salvage six dies of similar tool steels and shapes.

Welding of Stainless Steels

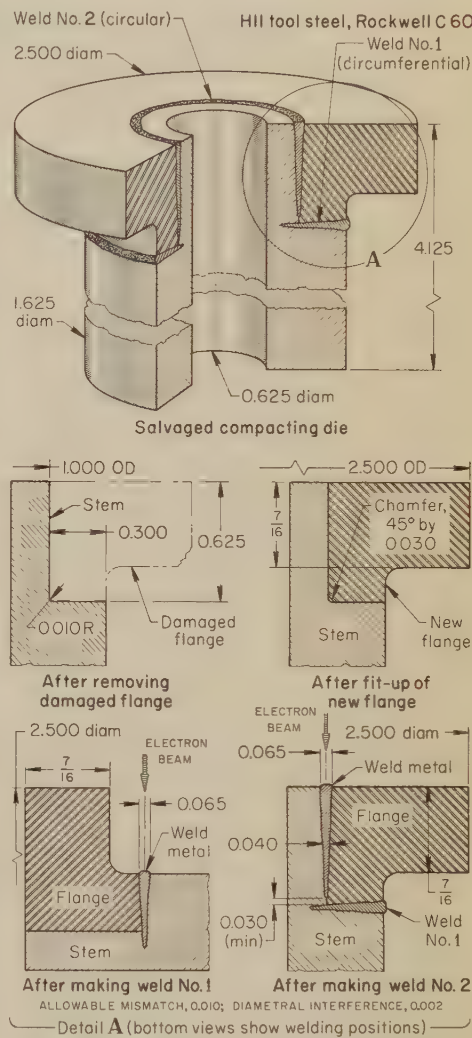
The properties and the welding metallurgy of the four groups of stainless steels are discussed in the article on Arc Welding of Stainless Steel, starting on page 245 of this volume.

Austenitic Stainless Steels. The high cooling rates typical of electron beam welding help to inhibit carbide precipitation, because of the short time during which the steel is in the sensitizing-temperature range.

Filler metal is used in welding joints that cannot be fitted together closely. The use of filler-metal preplacement is illustrated in Example 485, where a controlled-depth partial-penetration weld was required in a relatively open joint in type 304.

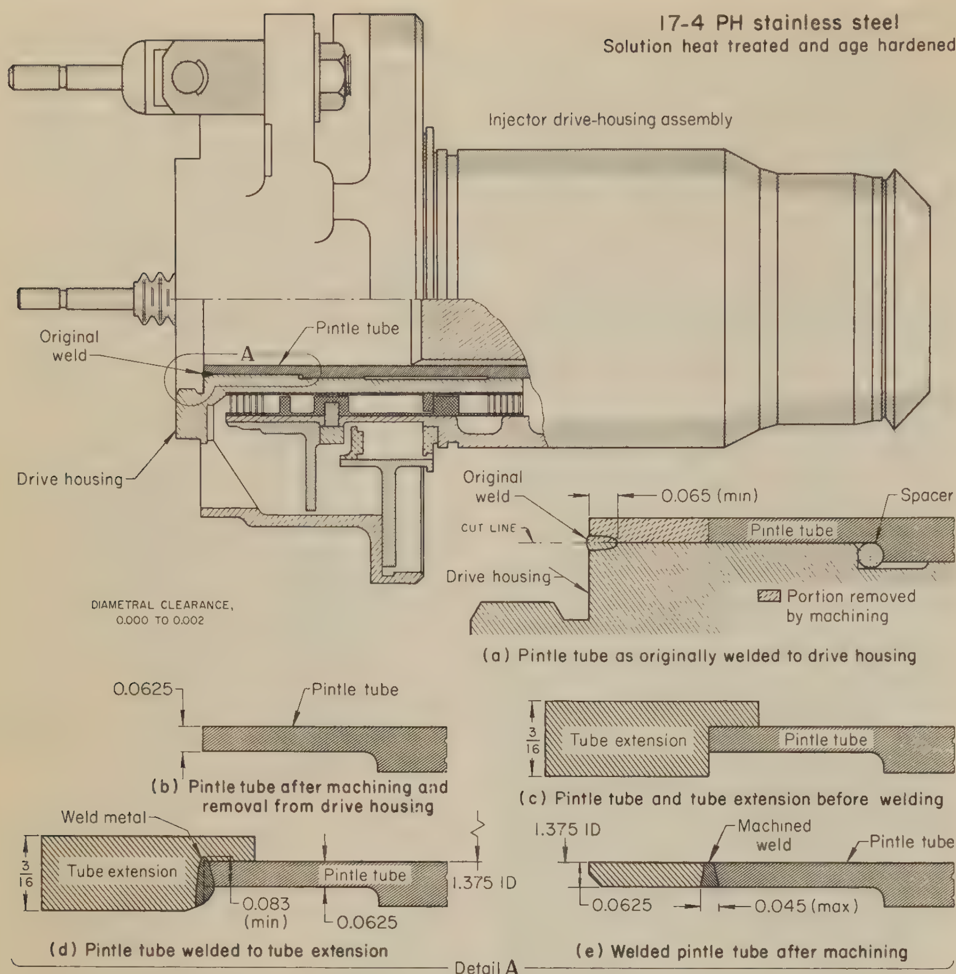
In attaching a rupture disk made of 0.002-in.-thick type 304 foil to a nozzle, severe burnback resulted when gas tungsten-arc welding was used. Electron beam welding solved the problem, as described in Example 476.

The welding of type 304 stainless steel to copper, to Hastelloy B, and to Inconel 600 is described in Examples 497, 499 and 501, respectively. An illustration of the range of heat control



Joint type	Circular and circumferential corner
Weld type	Square groove
Machine capacity	6 kw at 150 kv
Gun type	Fixed
Vacuum-chamber size	52 by 36 in. by 36 in. high
Maximum vacuum	10⁻⁶ torr
Fixtures	Rotatable positioner; three-jaw chuck
Preheat	500 F, for 2 hr at temperature, in a furnace
Welding power:	
Weld No. 1 (circumferential)	11 ma at 110 kv
Weld No. 2 (circular)	22 ma at 125 kv
Operating vacuum:	
During setup	2 × 10⁻⁴ torr
During welding	5 × 10⁻⁵ torr
Beam spot size	0.010 in.
Beam focal point	At surface
Welding speed:	
Weld No. 1 (circumferential)	30 ipm
Weld No. 2 (circular)	25 ipm
Postheat	500 F, for 2 hr at temperature

Fig. 43. Damaged die for compacting metal powders that was salvaged by electron beam welding a new flange to the stem without affecting the working surface and critical die dimensions (Example 488)



Welding Conditions for Salvaging

Joint type: Circumferential butt; rabbeted, self-backing	Welding power:
Weld type: Square groove	Tack welding: 90 kv at 1 ma
Machine capacity: 150 kv at 25 ma	Full welding: 110 kv at 5 ma
Gun type: Steigerwald; fixed	Welding vacuum: 4×10^{-5} torr
Maximum vacuum: 10^{-5} torr	Working distance: 6 in.
Vacuum-chamber size: 23 by 36 by 36 in.	Beam focal point: Sharp at pintle-tube surface
Fixtures: Special chuck(a); rotating positioner	Welding speed: 30 ipm (6.3 rpm)
	Welding time: 10 sec (automatic timer)

(a) Chuck consisted of a split aluminum ring designed to grip the critical area without distortion.

Fig. 44. Rocket-engine injector drive-housing assembly showing pintle-tube joint that was designed for salvage and reuse (Example 489)

possible with the electron beam is given in Example 631, in the article on Brazing of Stainless Steel.

Martensitic Stainless Steels. Although these steels can be electron beam welded in almost any heat treated condition, welding will produce a hardened, martensitic heat-affected zone. Hardness and susceptibility to cracking increase with increasing carbon content and cooling rate. Example 466 describes an application in which medium-vacuum electron beam welding replaced gas metal-arc welding.

Precipitation-hardening stainless steels can, in general, be electron beam welded to produce good mechanical properties in the joint. The semiaustenitic types, such as 17-7 PH and PH 14-8 Mo, can be welded as readily as the 18-8 types of austenitic stainless steel. The weld metal becomes austenitic during welding and remains austenitic during cooling. In the more martensitic types, such as 17-4 PH and 15-5 PH, the low carbon content precludes formation of hard martensite.

Some of the precipitation-hardening stainless steels have poor weldability because of their high phosphorus content. Steels 17-10 P and HNM are not usually electron beam welded.

An application that involved an unusually high degree of precision in joining 17-4 PH and 17-7 PH alloys is the flexure-bushing assembly described in Example 469. Another application involved a controlled-depth, partial-penetration weld in 17-4 PH alloy, as described in the following example.

Example 489. Electron Beam Welding of a 17-4 PH Part Designed for Salvage (Fig. 44)

Oxidizer pintle tubes, which formed part of the injector drive housings of lunar rocket engines, were designed for easy removal and salvage. A typical pintle tube, electron beam welded to its housing, is shown at the top in Fig. 44, and a cross-sectional detail of the joint in the initial assembly (as welded) is shown just below, at the right. Removal of the pintle tube was accomplished by machining away a short section of the tube at the weld. Salvage required fitting and welding on a new extension piece, which was machined to size, as shown in Fig. 44.

Reasons for this type of design were:

1 Pintle-tube alignment was crucial for optimum, smooth engine performance, and upon initial assembly, it was impossible to predict engine operating conditions and to weld the tubes for best alignment.
2 The precision-made housings cost approximately $10,000 each and required a long lead time. Therefore, salvage and reuse were highly desirable.

Electron beam welding was selected for both the initial and salvage welding operations because, in addition to providing the required mechanical properties, the low heat input minimized weld shrinkage and part distortion. Only the salvage operation is shown in Fig. 44 and dealt with in the accompanying table.

Neither preheating nor postheating was used in the salvage procedure. Both members of the joint were made of 17-4 PH stainless steel, solution heat treated and aged before assembly. No further heat treatment was permitted because close dimensional control would be lost.

The salvage welding, as indicated in the table with Fig. 44, required no special techniques. A used pintle tube was removed from its housing. The new extension piece was machined with a diametral clearance of 0.000 to 0.002 in. max, for fitting by hand. Parts were ultrasonically cleaned immediately after machining and wiped with acetone immediately before assembly.

A two-piece aluminum chuck was designed to hold the tube without affecting critical dimensions. The part was rotated, axis horizontal, under a fixed gun, without the use of beam oscillation. Four tack welds were made at 90° intervals. The welding cycle was automatically timed for one revolution plus a short overlap, automatic downslope being used to taper the power at the overlap. After machining excess material from the added section, the pintle tube was ready for reuse.

Welding of Heat-Resisting Alloys

Because of the marked differences in composition and weldability among heat-resisting alloys (nickel-base, iron-base, and cobalt-base), generalizations concerning electron beam welding of these alloys are not useful. Notes and references to examples follow.

Solid-Solution Nickel-Base Alloys. Hastelloy N, Hastelloy X and Inconel 625 are readily electron beam welded. In Example 499, Hastelloy B was welded to type 304 stainless steel. Inconel 600 was welded to itself and to type 304 stainless steel in Example 501.

Precipitation-hardenable nickel-base alloys that are rated good in weldability by the electron beam process include Inconel 700, alloy 718, Inconel X-750 and René 41. Alloy 718 can be welded in either the annealed or the aged condition. Inconel X-750 should be welded in the annealed condition, and René 41 should be welded in the solution-treated condition.

Alloys of this group that have fair weldability include casting alloys 713C and GMR-235 and wrought Udimet 700 and Waspaloy.

In Example 481, solution-treated René 41 was welded and then aged for 16 hr at 1400 F; selection of welding conditions for sound welds was important in this example, which involved two-tier welding at a separation of ½ in. In Example 465, a GMR-235 alloy casting was welded to case-hardened 8620 alloy steel.

Iron-Nickel-Chromium-Base Alloys. This group of alloys is also known as

the iron-base heat-resisting alloys. The most readily welded alloy of this group, using electron beam welding, is 19-9 DL, which has excellent weldability and on which the best results are obtained when preheating is used. Alloy N-155 has good weldability, and alloys 16-25-6 and A-286 are rated fair. Alloy A-286 is usually welded in the solution-treated condition; hot cracking may result if welding is done in the aged condition.

Cobalt-Base Alloys. HS-21 has good weldability in unrestrained joints (generally poor in restrained joints). Cast alloy HS-31 (X-40) has fair-to-good weldability, and alloy S-816 has fair weldability. Example 477 describes the successful electron beam welding of HS-25 castings when suitable procedures and precautions were used.

Welding of Refractory Metals

Electron beam welding is used for joining the refractory metals (tungsten, molybdenum, columbium, tantalum and their alloys), all of which have melting temperatures above 4000 F. The chief problem in welding these metals is embrittlement, caused by contamination. The electron beam process is especially well suited for welding refractory metals, because the vacuum prevents contamination.

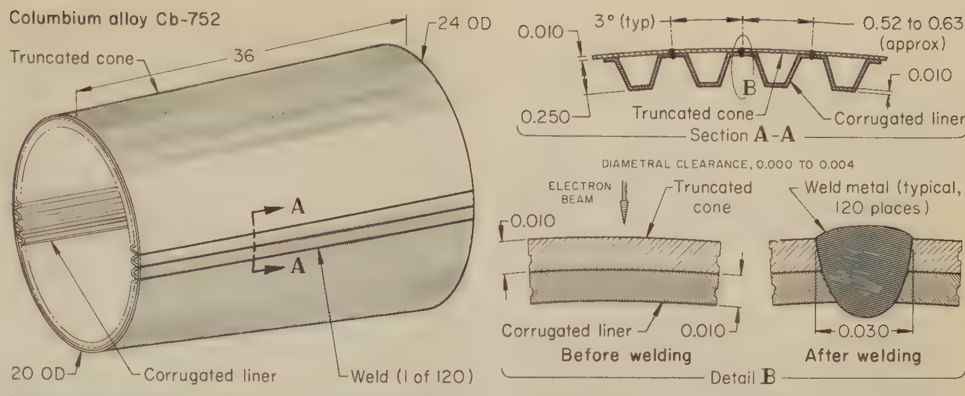
The main disadvantages of electron beam welding for joining the refractory metals are: (*a*) high welding speeds are not desirable in metals susceptible to thermal shock, (*b*) significant amounts of alloying elements that have high vapor pressures may be lost, and (*c*) some assemblies may require long times in the vacuum chamber, or forced cooling with inert gas to avoid atmospheric contamination.

Tungsten is the most difficult of the refractory metals to weld because of its high melting point (6170 F), sensitivity to thermal shock, and the room-temperature brittleness of the welds and of the heat-affected zone. Good and fair welding results have been reported for W-25Re and W-25Re-30Mo alloys, respectively.

Best results are obtained when assemblies are fixtured with the joint under compression during welding. Fixtures are often released after welding, to permit the weld to cool without restraint; if the weld is restrained during cooling, cracking is likely to occur. Preheating in the range of 1300 to 1400 F and postweld stress relieving at 1800 to 1900 F help to reduce stresses. Somewhat wider welds and lower welding speeds than are used for other refractory metals are desirable. Beam oscillation and pulsing are helpful. A 60-hertz deflection with an amplitude of 0.10 in. minimizes grain growth.

Molybdenum is almost as difficult to weld as tungsten. The cast weld structure is extremely brittle. Partly because of its lower melting point (4730 F), molybdenum has better thermal shock resistance than tungsten; thus, narrower welds and higher welding speeds can be used. The resulting lower heat input helps to reduce grain growth and intergranular segregation.

Preheating to about 400 F or higher is used with postweld stress relief at 1600



Joint and weld types	Lap; melt-through	Welding vacuum	10^{-5} torr
Machine capacity	60 kv at 500 ma	Beam focal point	At work surface
Gun type	Pierce; fixed	Working distance	3 in.
Maximum vacuum	10^{-7} torr	Welding speed	50 ipm
Vacuum-chamber size	112 by 50 by 62 in.	Number of passes	One
Fixtures	Semiautomatic indexing tool; traveling carriage	Preheat	None
Welding power	25 kv at 28 ma	Postweld heat treatment	Stress relieve at 2150 F for 90 min in an inert atmosphere

Fig. 45. Truncated cone and corrugated liner (members of a missile-body component) that were joined by electron beam melt-through welding, under conditions in table (Example 490)

to 1800 F. Beam oscillation is used to overcome undercut and surface roughness, which commonly occur.

Several molybdenum alloys have been electron beam welded, notably Mo-0.5Ti and TZM alloy (Mo-0.5Ti-0.08Zr-0.02W). Typical conditions used in butt welding 0.050 to 0.100-in.-thick Mo-0.5Ti are:

Preheat	600 F
Welding power	135 kv at 10 ma
Welding speed	27 ipm
Beam oscillation	60 hertz with 0.005-in. transverse deflection
Weld depth-to-width ratio	4
Heat-affected-zone depth-to-width ratio	2.2
Weld-zone grain size	ASTM No. 6

Columbium, which melts at 4474 F, is easier to weld than molybdenum or tungsten. Gas tungsten-arc welding is often used, but electron beam welding provides better protection, narrower welds, and lower heat input. Preheating is not necessary, but postweld vacuum stress relief is used to restore ductility and toughness, especially in the columbium alloys.

Unalloyed columbium is easily electron beam welded, but has relatively low strength. More alloys have been developed, mainly for higher strength, than for the other refractory metals. Alloying usually reduces weldability, but most weld joints in alloys retain about 75% efficiency, and good structural properties can be obtained for service temperatures in the range of about 2000 to 3000 F, depending on the alloy. Chill tooling is often used, but copper, nickel and stainless steel should be avoided, to prevent contamination of the weld metal.

In the example that follows, good weld ductility was required in joining a missile cone to a missile liner, because of differential thermal stresses in service and the need to prevent distortion.

Example 490. Electron Beam Melt-Through Welding of Columbium Alloy Cb-752 (Fig. 45)

Both members of a missile-body component (a truncated cone and a corrugated liner) were made of columbium alloy Cb-752 (0.03 C max, 0.0020 H max, 0.04 O max, 0.01 N max, 2.0 to 3.0 Zr, 9.0 to 11.0 W, rem Cb). As shown in Fig. 45, the liner corrugations ran from the top of the cone to the base, parallel to the sides, making 120 equally spaced contacts with the inside surface of the outer shell. The assembly required 120 longitudinal welds about 0.52 to 0.63 in. apart (3° of arc) to join the two components at the contact surfaces. There were no weld grooves; each component was formed from a continuous sheet.

Maintaining the structural integrity of the assembly for service requirements involving high-temperature cycling was the major fabricating objective.

Electron beam welding under relatively high vacuum was selected for this application because the absence of an atmosphere had been found to be more effective in avoiding embrittlement than the use of an inert gas. In addition, the smaller welds and higher welding speeds obtained minimized distortion and structural changes due to the welding heat. Power was easily adjusted to achieve a continuous weld that fully penetrated both sheets in a single pass, using the keyhole technique.

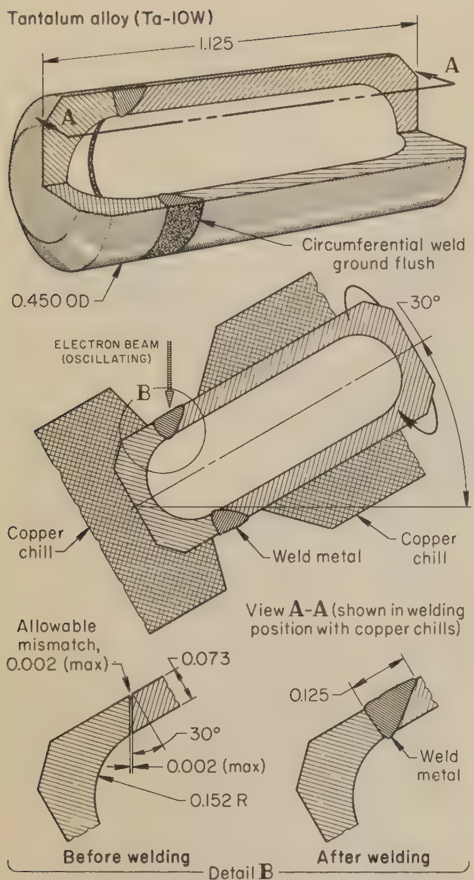
The alloy was in the annealed condition before welding and required stress-relief heat treatment after welding. Preweld cleaning consisted of chemical etching and wiping with alcohol just before welding. All joint surfaces were machined or drawfiled. White gloves were worn for all handling of parts between final cleaning and welding.

The two components were assembled in a semiautomatic indexing fixture in which the hold-down bars were changed manually after completion of each longitudinal weld. For each weld, therefore, a separate vacuum pumpdown was required. As shown in section A-A of Fig. 45, clearance tolerances at the surfaces to be welded were held as close to intimate contact as was feasible. Each end of the cone was machine trimmed after welding.

Details of the equipment and machine settings used for this operation are summarized in the table with Fig. 45.

To determine the effectiveness of the welding procedure, the following tests were made. Weld surfaces were examined by liquid-penetrant inspection. Radiographic inspection was used to detect cracks and voids. Weld joints, with weld reinforcement removed, were bent over an arc of 105°, using an 0.080-in.-diam mandrel. Both root and face bends were required to show no cracks when examined visually at 10×.

Tantalum is the most easily weldable of the four refractory metals. Because of its high melting point (5425 F) and good thermal conductivity, thicknesses of 0.060 in. or more must be rapidly



Joint type	Circumferential butt
Weld type	30° slant groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald triode; fixed
Filament	Tungsten hot wire
Vacuum-chamber size	23 by 36 by 23 in.
Maximum vacuum	10^{-5} torr
Fixtures	Three-jaw chuck; spindle; copper chills
Welding vacuum	10^{-4} to 5×10^{-5} torr
Pumpdown time	5 min
Welding power	120 kv at 10 ma
Preheat power	120 kv at 5.5 ma
Number of passes	Four (three preheating, one welding)
Beam focal point	Sharp at surface
Beam spot	0.015-in. diameter (est)
Beam oscillation	0.040-in. linear deflection at 60 hertz, in direction of weld
Power density	7 megawatts per square inch
Working distance	6 in.
Welding speed	45 ipm (31.8 rpm)
Parts per chamber load	One

Fig. 46. Tantalum alloy capsule that was full-penetration welded for high creep-rupture joint strength (Example 491)

heated to high temperatures for welding. Copper chills are used to avoid distortion and weld sagging and to shorten the time the assembly has to remain in the vacuum chamber, thus limiting grain growth.

Weldability of tantalum alloys containing other refractory elements is somewhat lower than that of unalloyed tantalum. Because of high vapor pressure, alloys containing vanadium are better welded by the gas tungsten-arc process. One of the most common alloys is Ta-10W, which was welded in the following example.

Example 491. Full-Penetration Welding of Ta-10W for High Creep-Rupture Strength (Fig. 46)

Electron beam welding was selected for making the closure weld in the capsule shown in Fig. 46. Requirements called for a full weld with complete joint penetration, a smooth, spatter-free interior, and high creep-rupture strength. The Ta-10W joints could have been welded by the gas tungsten-arc process, in an inert atmosphere in a welding chamber, but joint properties probably would have been lower. Also, the gas tungsten-arc process, with larger weld zones, greater heat input, and a wider heat-affected zone, was likely to increase the extent of grain growth, thereby reducing creep-rupture strength. Another factor favoring the selection of electron beam welding was that welding under vacuum minimized gaseous contamination, to which the alloy was highly susceptible.

Successful production of the capsules depended on a consistently reproducible welding procedure, as evidenced by consistency of results in a series of qualification tests. Although such a procedure was developed, special precautions were needed to control root-face "suck-back", internal spatter, and weld-face underfill. For high service reliability, each welded capsule was inspected by liquid-penetrant and radiographic methods; in addition, one capsule in ten was tested destructively for strength and was examined metallurgically. Details of the welding procedure and sequence of operations are described below.

The 30°-slant butt joint shown in detail B of Fig. 46 was designed for self-aligning, accurate fit-up and to facilitate radiographic examination. After careful machining to avoid broken joint edges, the surfaces were cleaned by wiping with acetone. Dye marks were placed on one side of the joint to aid in aligning the beam on the joint, because the close fit-up made it difficult to distinguish the joint from machining marks. The dye, a film only a few angstroms thick, vaporized on heating, without contaminating the weld.

The parts were fixed in copper chill blocks and assembled by chucking and aligning to tolerance in a spindle set at a 30° angle, as shown in Fig. 46, view A-A. During vacuum pumpdown, beam alignment was set within 0.002-in. runout by sighting a low-power beam with a 20-power optical attachment.

Copper chills were used to prevent distortion and to shorten cooling time under vacuum, thus limiting grain growth. Adequate cooling time under vacuum was necessary because the alloy was susceptible to atmospheric contamination at elevated temperatures. The relatively low heating and cooling rate of the alloy, together with the absence of convection cooling in the chamber, would have considerably delayed vacuum release if chills had not been used. Because the tantalum alloy was not hardenable by heat treatment, hardenability, as such, was not a factor in preheating or chilling.

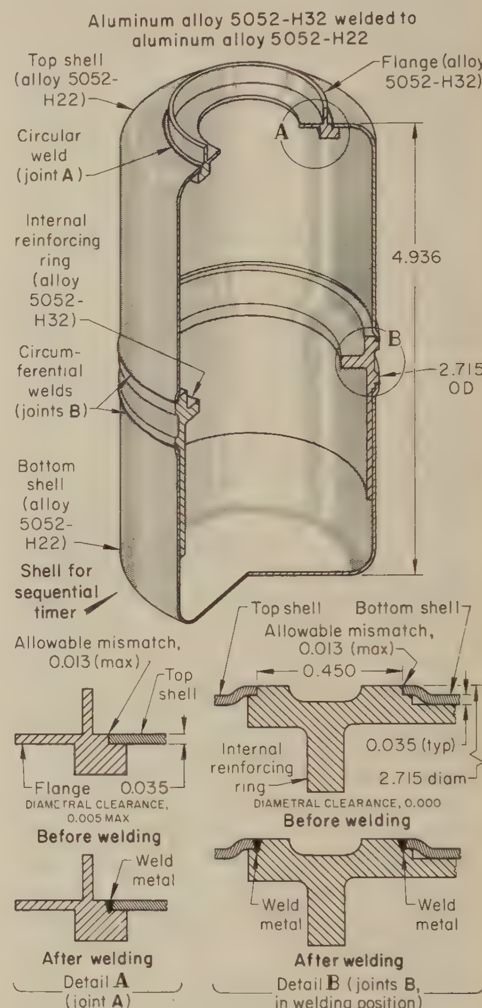
Both preheating and beam oscillation were found to be necessary to obtain the required weld shape on the inner and outer weld surfaces, and to reduce internal spatter. One of the problems in welding this alloy, the tendency of the weld to draw back from the root into the joint, due to the very high surface tension of the molten metal, aided possibly by an internal pressure buildup, and another problem, filling the hole that was created on starting the weld, were overcome by preheating and beam oscillation. Although both procedures added heat, the travel speed (45 in. per minute) kept welding heat input at 1.6 kilojoules per inch, the effect of which was reduced by the chills.

Preheating was accomplished by making three passes with the electron beam at low power (partially defocused). After the third pass, power was increased for welding, which was done in a single pass. Both preheating and welding were done with the beam oscillating linearly in the direction of the weld. Welding conditions are given in the table accompanying Fig. 46.

The welding problems mentioned above were reduced to an acceptable level, but not eliminated. Because quality assurance, rather than high production rate, was the objective, only one capsule was welded per pumpdown. Sampling for destructive testing was relatively high, at 10%, indicating the application to be too critical for reliance on nondestructive testing alone.

Welding of Aluminum Alloys

Single-pass full-penetration welds with depth-to-width ratios of more than 20 to 1 have been made in 6-in.-thick aluminum alloy plates.



Joint type, joint A	Circular butt; rabbeted, self-backing
Joint type, joints B	Circumferential butt; rabbeted, self-backing
Weld type (all joints)	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald triode; fixed
Vacuum-chamber size	36 by 23 by 30 in.
Maximum vacuum	10^{-5} torr (approx)
Fixtures	Universal chuck; lathe-type spindle; carriage with x-y drive
Filler metal	None
Welding power:	
Joint A, tack welding	110 kv at 2.5 ma
Joint A, full welding	130 kv at 5 ma
Joints B, full welding	120 kv at 5.5 ma
Welding vacuum	10^{-4} torr, approx (all welds)
Beam focal point	Sharp at surface (all welds)
Beam oscillation	0.010-in. diameter at 1000 hertz(a)
Welding speed:	
Joint A	77 ipm (14 rpm)
Joints B	119 ipm (14 rpm)
Working distance	7.5 in. (all welds)(b)
Production rate	4 parts per hour

(a) Circular deflection. (b) Measured from the top of the chamber to the workpiece.

Fig. 47. Sectioned view of the shell of a sequential timer, and details of the circular and circumferential joints welded by the electron beam process (Example 492)

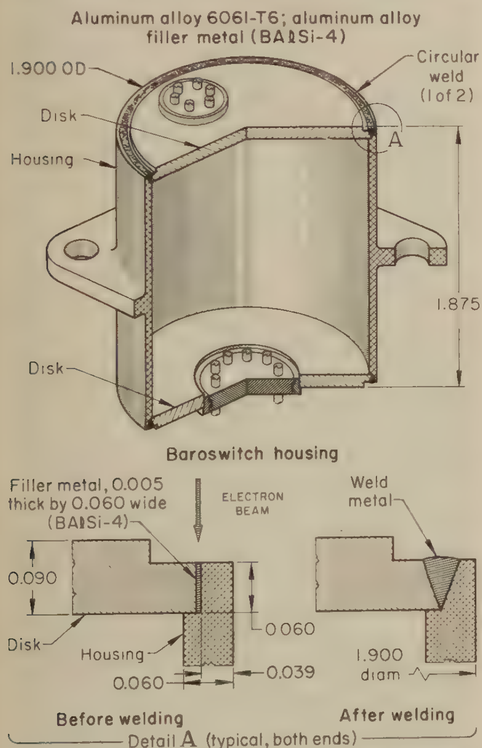
The low heat input, narrow heat-affected zone, and short heat cycle result in minimum decrease in mechanical properties, especially in assemblies of some of the heat treatable alloys.

Non-Heat-Treatable Alloys. The mechanical properties of electron beam welds in the non-heat-treatable alloys (1*xxx*, 3*xxx*, 5*xxx* series) are virtually the same as those obtained by gas tungsten-arc welding. If the alloy is in a strain-hardened condition, the weld properties closely approach the annealed properties of the base metal.

Obtaining maximum joint strength is not the principal objective in all applications. In welding nuclear fuel elements, as in Example 474, obtaining a tight closure and a narrow full-penetration weld were the objectives. In the application described in the example that follows — welding a thin-wall enclosure made of alloy 5052 in the strain-hardened condition — freedom from distortion was a critical factor.

Example 492. Welding a Thin-Wall Aluminum Alloy 5052 Assembly (Fig. 47)

Figure 47 shows the structural details of a shell for a sequential timer. The circular joint and the two circumferential joints



Joint type	Circular corner; rabbeted, self-backing
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald triode; fixed
Vacuum-chamber size	36 by 23 by 30 in.
Maximum vacuum	10^{-5} torr
Fixtures	Universal chuck, turntable
Filler metal	0.005-in.-thick foil of BAlSi-4
Welding power	110 kv at 4 ma
Welding vacuum	10^{-4} torr, or less
Beam focal point	Sharp at surface
Beam oscillation	0.010-in. diameter at 1000 hertz(a)
Welding speed	101.2 ipm (18 rpm)
Working distance	8 in.(b)
Production rate	5 parts per hour

(a) Circular deflection. (b) Measured from the top of the chamber to the workpiece.

Fig. 48. Baroswitch housing that was electron beam welded with preplaced filler metal, to avoid cracking (Example 493)

used to fabricate the assembly were electron beam welded because small, accurate, partial-penetration welds were required, to minimize distortion and yet provide hermetic seals.

The non-heat-treatable 5052 base metal was strain hardened and partially annealed (H22), or strain hardened and stabilized at low temperature (H32), for the various components, as shown in Fig. 47. Preheating and postheating were neither desirable nor necessary. Unlike some heat treatable alloys (see Example 475), alloy 5052 did not require a filler-metal addition to prevent cracking.

After components were formed and machined, they were cleaned and degreased. Just before assembly for welding, components were brushed clean of oxide film with a stainless steel wire or a fiber glass brush, and wiped clean of dust with a solvent. No fingerprints were permitted on cleaned surfaces.

Assembly and welding of the unit were done in two stages, each stage requiring a separate pumpdown. First, the top flange and top shell were assembled by means of an internal fixture mounted on a turntable in the vacuum chamber. An external fixture lightly held the shell in position for tack welding. The chamber was evacuated and the joint (joint A in Fig. 47) was optically aligned (using a 20-power telescope) under the fixed beam, with runout not exceeding 0.001 in. The telescope was equipped with a reticle graduated in thousandths of an inch. With the assembly rotating about its vertical axis, four tack welds were made, with circular beam oscillation, at 90° intervals. A preset weld timer controlled tack-weld length.

Full welding of each joint was done by starting rotation and holding the "on" button for one complete revolution, and then pressing the "off" button. Automatic current downslope tapered beam power to zero over a very short distance of approximately 5° of revolution. Detail A in Fig. 47 shows joint A before and after welding, and the accompanying table gives the machine settings used for all welding operations.

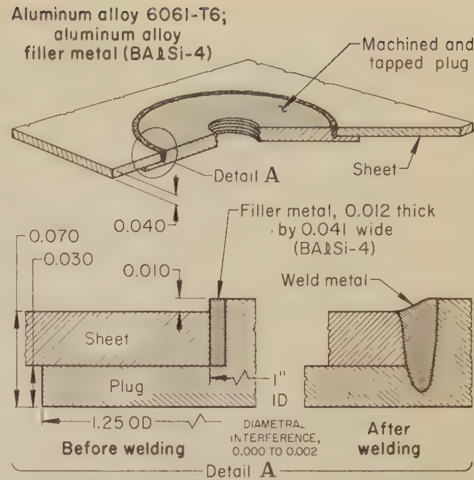
Vacuum was released, the subassembly was removed, and the remaining components were assembled. The assembly was chucked (axis horizontal) between the headstock and tailstock of a lathe-type spindle, with sufficient pressure to eliminate the need for tack welding. The two circumferential joints (joints B in Fig. 47) were welded, with beam oscillation, in one pumpdown. The first joint was optically aligned and welded, and then the second joint was moved into alignment by the motor-driven carriage that supported the entire fixtured assembly. Details of joints B, before and after welding, are shown in detail B in Fig. 47; welding conditions are included in the accompanying table.

Completed enclosures had to meet helium leak-rate tests with rates not exceeding 10^{-7} cu cm helium per second at 1 atm pressure. Periodically, three enclosures were selected for destructive testing, which consisted of tension testing and macroscopic examination for weld soundness. Similar tests were also made on a regular sampling basis of one part out of twenty.

Heat treatable alloys of series 2*xxx*, 6*xxx* and 7*xxx* are crack sensitive to varying degrees when welded. The condition of the zone immediately adjacent to the weld is critical in determining weldability.

The 6*xxx* alloys are only slightly affected by the heat cycles of electron beam welding. Alloys 2219, 7039 and 7005 appear to be the least affected of the alloys of their respective series. The techniques used to prevent cracking in electron beam welding the heat treatable aluminum alloys are:

1 Special care in preweld cleaning to avoid porosity and oxide inclusions in the weld metal



Joint type	Circular butt; rabbeted, self-backing
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Steigerwald; fixed
Maximum vacuum	10^{-5} torr
Vacuum-chamber size	23 by 36 by 36 in.
Filler metal	0.012-in.-thick BAlSi-4
Fixtures	Turntable; copper chills
Welding power:	
Tack welding	110 kv at 4.5 ma
Full welding	110 kv at 7 ma
Welding vacuum	5×10^{-5} torr
Beam oscillation	Circular, 0.1-in. diameter at 35 hertz(a)
Beam focal point	Sharp at surface
Working distance	6 in.
Welding speed	100 ipm (31.8 rpm)

(a) Using a 1-millisecond pulse width

Fig. 49. Repair of a partly processed sheet metal part, showing a replacement plug welded in place, using preplaced filler-metal foil (Example 494)

2 Prestressing joints in compression by using interference fits when possible

3 Use of a ductile filler metal, usually in the form of a thin strip preplaced in the joint, which will yield under shrinkage stresses and fill joint openings

4 Selection of beam power, beam spot size, and welding speed to create as narrow welds as practical during short welding heat cycles, thus avoiding excessive grain-boundary melting

5 Use of postweld heat treatment to restore the strength and ductility of the weld and heat-affected zones

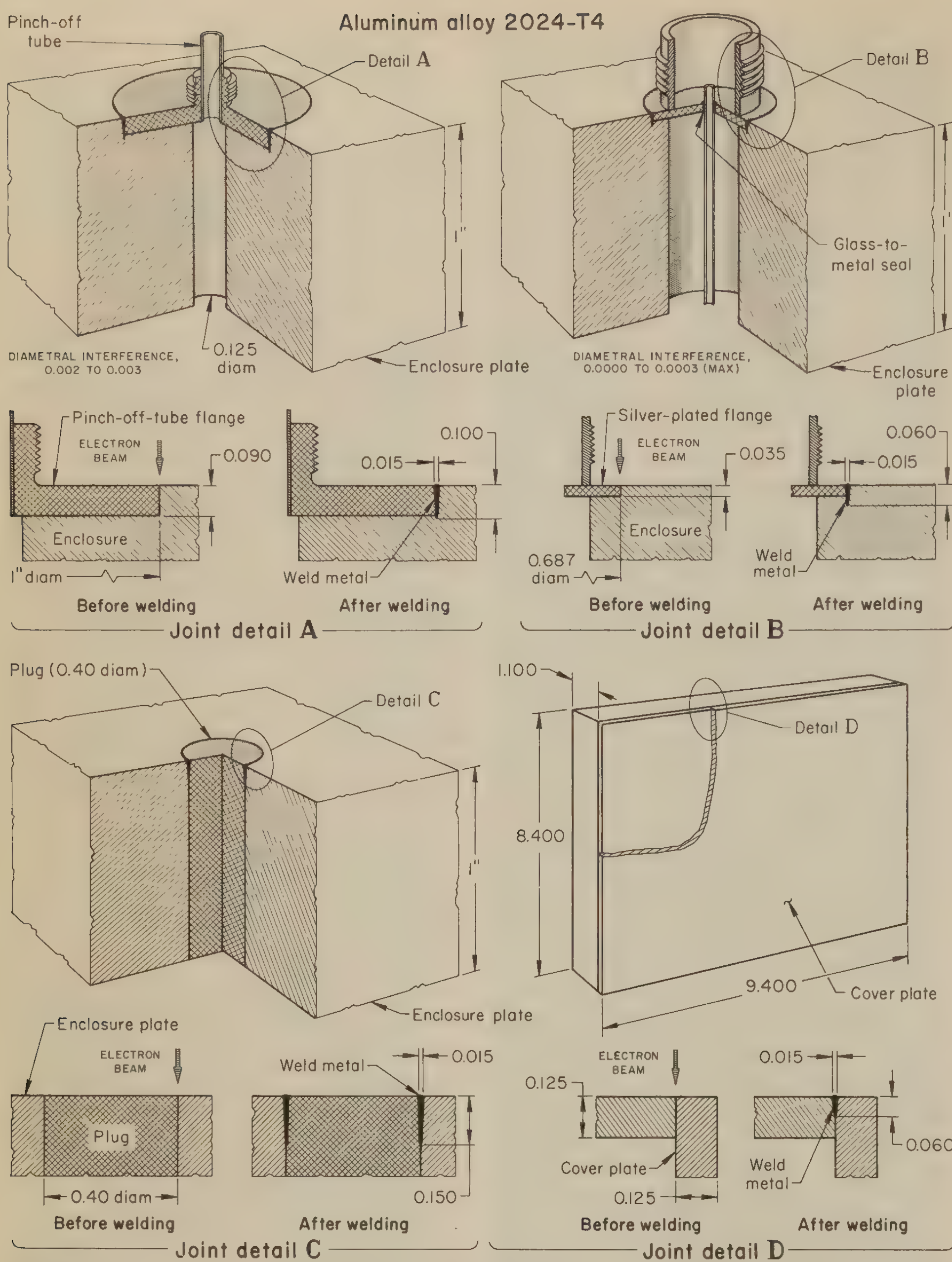
6 Other techniques include designing or locating joints to be free of externally imposed restraints, reinforcing of joint areas and, when possible, welding in the solution-treated condition, with postweld aging.

In the highly critical welding of loaded fuze assemblies made of alloy 6061-T6 (Example 475), a brazing sheet giving good ductility was used as filler metal. In the next example, foil filler metal was used to prevent cracking of an alloy 6061-T6 instrument housing.

Example 493. Use of Filler Metal To Prevent Cracking in Welding a Heat Treatable Aluminum Alloy (Fig. 48)

The baroswitch housing shown in Fig. 48, which supported and protected an internal pressure-sensing and switching mechanism, was made of alloy 6061-T6. This material, like other heat treatable aluminum alloys, was crack-sensitive when welded to itself, but no cracking could be tolerated in this application. The cracking problem was solved by use of a suitable filler metal in the form of 0.005-in.-thick foil preplaced in the joints.

The filler metal selected was BAlSi-4, an aluminum alloy containing about 12% silicon. The filler-metal foil was cut into



	Joint detail A	Joint detail B(a)	Joint detail C	Joint detail D
Joint type	Circular butt; rabbeted, self-backing	Circular butt; rabbeted, self-backing	Circular butt	Corner
Weld type	Square groove	Square groove	Square groove	Square groove
Joint thickness	0.090 in.	0.035 in.	1 in.	0.125 in.
Welding power(b)	60 kv at 8 ma	60 kv at 6 ma	60 kv at 8 ma	100 kv at 10 ma
Welding vacuum	10^{-4} torr	10^{-4} torr	10^{-4} torr	10^{-4} torr
Pumpdown time	5 min	5 min	5 min	5 min
Beam focal point	Workpiece surface	Workpiece surface	Workpiece surface	(c)
Working distance (d)	5 in.	5 in.	6 in.	5 in.
Welding speed	31 ipm (10 rpm)	35 ipm (16 rpm)	20 ipm (16 rpm)	50 ipm
Beam oscillation	None	None	None	(e)
Number of passes	One, 60° downslope	One, 60° downslope	One, 60° downslope	One
Preheat, postheat	None	None	None	None

(a) Flange in joint detail B was silver plated. (b) The same machine was used for all joints; see text of example for description. (c) Beam focal point was about ½ in. above the workpiece surface. (d) Distance from the heat shield to the work. (e) 0.015-in. diameter, circular, at 500 hertz.

Fig. 50. Four types of joints used in fabricating an electronic-detector package (Example 495)

strips 0.060 in. wide, deburred by drawing over the edge of a sharp knife, cleaned with solvent, and wiped dry just before use. The strips were hand fitted into the joint, which had previously been machined to allow about 0.001-in. clearance after fitting. To allow for machining variations, filler-metal thicknesses of 0.004 and 0.006 in. were also available.

Using the BAlSi-4 filler metal, the desired weld-metal composition and properties were obtained.

In this application, the procedures for preweld cleaning, assembly, fixturing, beam alignment and welding were essentially the same as those described in Example 475. Tack welding was not used; instead the weld was made at a much higher speed, reducing the heat input considerably (0.26, as compared to 0.61 and 0.75, kilojoules per inch). High-speed welding also helped to prevent cracking.

Welding conditions are given in the table accompanying Fig. 48.

Repair welding entails the same procedures and requires the same care as assembly welding, although the length of repair welds is usually shorter. Repair of 6061-T6 sheet by welding a replacement plug of the same material is described in the following example.

Example 494. Use of a Plug and Preplaced Filler Metal To Repair Small Defects in Aluminum Alloy Sheet (Fig. 49)

Improperly drilled or tapped holes in partly processed precision components were repaired by cutting out the defective region and welding in a small plug, using the electron beam process. Care was required to avoid cracking and distortion, because of high joint restraint (the plug was press fitted). Figure 49 shows a typical repair made in alloy 6061-T6 sheet. In this instance, repair was complicated because a small tapped hole was to be located within the repair area, and tapping required a plug of the 6061-T6 alloy, for hardness.

A high-silicon filler metal was used, to avoid cracking due to hot shortness. If a plug of softer material, such as aluminum alloy 1100, could have been used, added filler metal would not have been required. A plug made entirely of a high-silicon filler metal, such as 4043 or 4047, also would have been satisfactory, but these materials were not readily available, except in wire and sheet forms. Filler metal used in this repair was a 0.012-in.-thick shim of BAlSi-4 brazing filler metal (4047 alloy).

Preparation for the repair consisted of cutting a 1-in.-diam hole to remove the defective area and machining a plug with a 0.002-in. max interference (Fig. 49). The weld area was carefully cleaned to remove all traces of oil and oxide. The filler metal was wire brushed with stainless steel bristles, cut to size, and fitted tightly around the plug. The plug was then inserted in the hole by means of a press fit.

After mounting the workpiece on a variable-speed turntable in the vacuum chamber, with copper chills around the plug, and aligning the beam on the joint, the chamber was evacuated. Four tack welds, each 0.20 in. long, were made to anchor the filler metal and hold the plug in alignment during welding. The tack welds were allowed to cool, and welding was done in a single pass, using automatic power downslope for approximately ⅜ in. after passing the starting point. The crossover from weld stop to start had been the most difficult area in controlling cracking, porosity and incomplete fusion when the welding schedule was being developed, prior to the actual repair. Beam oscillation and the conditions that produced satisfactory welds are summarized in the table with Fig. 49.

The view at the top in Fig. 49 shows the completed repair, with the plug machined flush on the outer surface, and the newly tapped hole. The inner projection of the plug was machined flush only when necessary for clearance.

Welding practice in joining cast aluminum alloys to themselves or to wrought alloys is generally the same as for joining wrought alloys. In Example 480, a difficult-access repair in a part fabricated from the heat treatable casting alloy 356 was made by welding a sleeve within an oversize bore.

Alloy 2024, one of the more crack-sensitive alloys of the 2xxx series, is almost never welded. In the manufacture of aircraft pontoons made of stretch-formed 2024 alloy, for instance, welding is prohibited before or after

forming. When fabricating conditions permit no alternative, however, special techniques can be used, as is described in Example 498.

In the example that follows, satisfactory seal welds were made without using filler metal.

Example 495. Electron Beam Welding of Aluminum Alloy 2024-T4 for Hermetic Sealing (Fig. 50)

Fabrication of a rush order for electronic-detector packages called for electron beam welding of four joints between components made of aluminum alloy 2024-T4. This alloy was used for the enclosures because the connector components were quickly available in the alloy. The chief objective in fabrication was to make a weld that would pass a helium leak test, rather than to develop the full strength properties.

Time was not available for development of the optimum procedure; machine settings were adopted as soon as results proved satisfactory. All welds were made using a high-voltage machine with a fixed gun of the triode type. The machine was rated at 150 kv at 40 ma. The vacuum chamber, 36 by 23 by 30 in. in size, was capable of a maximum vacuum of 5×10^{-5} torr. Fixtures included holding clamps, a travel carriage, and an eccentric circle generator. Machine settings for each weld are given in the table with Fig. 50, and the joints are shown in Fig. 50. Other factors affecting the procedure were as follows.

Joint A. Joining a pinch-off tube to the enclosure plate required a square-groove weld in a 1-in.-diam circular joint, as shown in the upper left of Fig. 50. The enclosure plate was recessed to a depth (0.090 in.) equal to the thickness of the pinch-off-tube flange with an interference on the diameter of 0.002 to 0.003 in. for a press fit.

During welding, the circular path of the joint was tracked by the beam, using a circle generator. This device consisted of a welding table driven in the horizontal plane by two eccentric drives so as to generate a circle by translation rather than by rotation. By selecting precalibrated settings on the control unit, any circle up to 2 in. in diameter could be accurately described by the table and any workpiece on it.

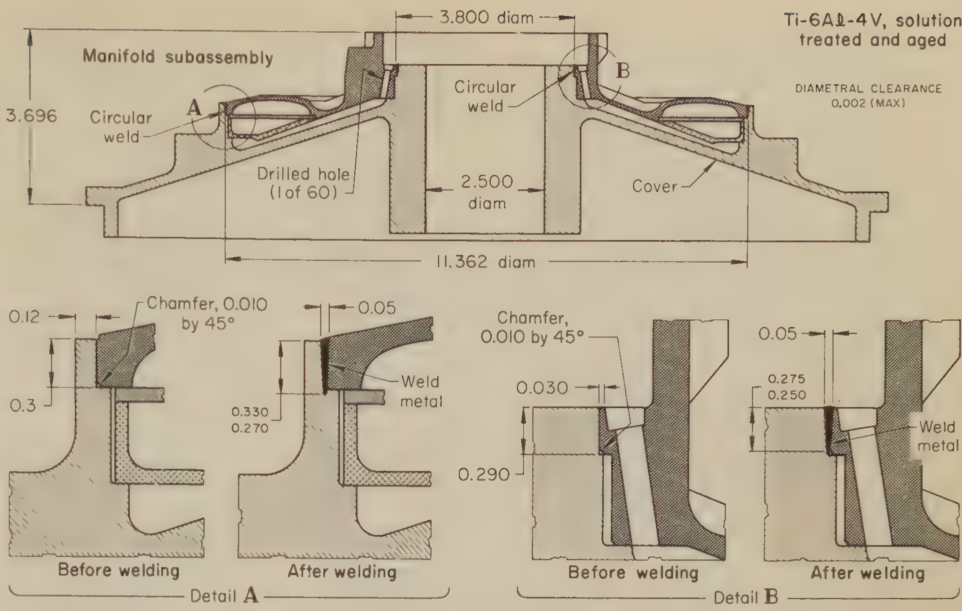
No difficulty was encountered in meeting leak-rate requirements using the conditions shown in the table with Fig. 50.

Joint B. From a welding point of view, the radio-frequency connector of the electronic-detector package differed from the pinch-off-tube component in these respects: (*a*) the flange was silver plated and was thinner (0.035 in.), (*b*) the flange diameter was smaller (0.687 in.), and (*c*) the flange contained a glass-to-metal seal, easily damaged by heat. Joint tracking was done by the circle generator.

Initially, welding was attempted by positioning the flange on the flat surface of the enclosure plate and fusing the flange edge to form a fillet weld. A satisfactory weld was obtained at a current of 8 ma, but the heat sometimes cracked the glass-to-metal seal. At lower currents, weld cracking occurred. By recessing the plate, using an interference of 0.0003 in. max on the diameter, it was possible, after a light press fit, to weld the joint at 6 ma without damaging the seal.

Joint C. Holes 0.395 to 0.397 in. in diameter were drilled in the 1-in.-thick enclosure plate during fabrication, to provide access for internal machining. The holes were sealed by welding in 0.40-in.-diam plugs that had been pressed in place. Depth of penetration was not critical for these welds, so long as they proved tight in leak testing. Partial-penetration welds only 0.150 in. deep proved satisfactory. There were no particular problems in meeting requirements when the circle generator was used together with the conditions shown in the table with Fig. 50.

Joint D. The cover plate of the rectangular electronic-detector package called for four welds to seal the unit hermetically. A separate vacuum pumpdown was required for each weld. Rectilinear motion was obtained by means of a track-guided carriage, which was part of the equipment. The most critical portions of these welds were at the package corners, where the beam entered and left the joint, resulting in weld intersection. Careful use of starting and runoff tabs was necessary to obtain leak-tight joints. Tabs were lightly tack welded, so that they could be broken off after welding and the rough spots filed smooth. Sometimes, repair welding was necessary. The use of a softer beam focus and a circular beam oscillation was found desirable. Welding conditions for joint D are listed in the table that accompanies Fig. 50.



Joint type ....Circular corner, self-aligning	Gun type ....Steigerwald triode; fixed
Weld type ....Square groove	Maximum vacuum ....10^{-5} torr
Machine capacity ....150 kv at 40 ma	Vacuum-chamber size ....23 by 36 by 36 in.

	Weld A	Weld B(a)
Welding power:		
Tack welding	110 kv at 4 ma	110 kv at 4 ma
Full welding	130 kv at 20 ma	130 kv at 16.9 ma
Working distance	6 in.	5¼ in.
Beam focal point	At work surface (all welds)	At work surface (all welds)
Beam oscillation(b)	0.043 in., at 1000 hertz	0.043 in., at 1000 hertz
Welding speed	61 ipm (1.7 rpm)	60 ipm (5 rpm)

(a) Holes near weld B were chilled with copper inserts and a copper ring that was fitted over the holes. (b) Oscillation was in a straight line (rectilinear), and tangential to joint circle.

Fig. 51. Manifold subassembly of a rocket-engine fuel injector, showing the two major joints welded by the electron beam process. Weld shown in detail B was especially critical because of proximity to drilled holes. (Example 496)

Welding of Copper and Copper Alloys

The electron beam welding of copper and its alloys is influenced by the same factors that affect the arc welding of these metals (see the article on Arc Welding of Copper and Copper Alloys, pages 337 to 357 in this volume). The high thermal conductivity of copper causes less difficulty in electron beam than in arc welding.

Molten metal may be expelled from the weld joint during electron beam welding of nondeoxidized coppers (especially alloy 110, ETP copper), causing spatter and uneven weld surfaces, but this can usually be remedied by the use of a cosmetic pass. The vacuum environment avoids possible hydrogen embrittlement; nevertheless, root voids and porosity still can occur.

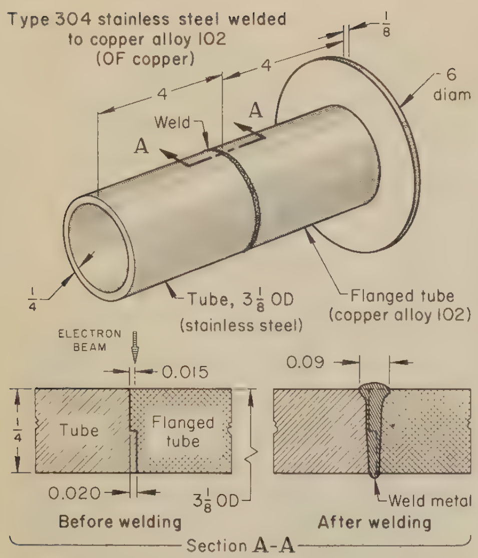
The presence of low-melting elements ordinarily makes the welding of free-machining copper alloys impractical, and the volatility of zinc prevents the welding of the brasses and other zinc-containing copper alloys. The remaining copper alloys shown in Table 1 on page 338 in "Arc Welding of Copper and Copper Alloys" can be electron beam welded without any unusual problems, except for alloy 175 (high-conductivity beryllium copper), for which the welding conditions must be controlled within a very narrow range to produce sound welds, and special safety precautions must be taken because of the toxicity of beryllium.

Applications. The electron beam welding of copper is described in Examples 482, 497 and 502 in this article.

Welding of Magnesium Alloys

Electron beam welding is used to a limited extent, chiefly for repair, on commercial wrought and cast magnesium alloys that contain less than 1% zinc. The relative suitability of alloys for electron beam welding is generally the same as for arc welding, as discussed in the article on Arc Welding of Magnesium Alloys (pages 358 to 365).

Special techniques and close control of operating variables are needed in order to prevent voids and porosity at the root of the weld, because of the high vapor pressure of magnesium, which has the lowest boiling point (2025 F) of any commonly welded metal. This difficulty is aggravated by the presence of zinc, which has a still lower boiling point (1663 F). It is ordi-



Joint type	Circumferential butt; double-rabbeted, self-aligning
Weld type	Square groove
Welding power	22 kv at 100 ma
Beam spot size	0.03-in. diameter
Beam focal point	At work surface
Working distance	1¾ in.
Welding speed	37 ipm
Welding vacuum	10^{-4} torr
Heat input	3.57 kilojoules per inch
Number of passes	One(a)

(a) Plus a cosmetic pass, which was applied later by manual adjustment of beam power

Fig. 52. Welding of a copper alloy 102 flanged tube to a type 304 stainless steel tube (Example 497)

narily impractical to electron beam weld magnesium alloys that contain more than 1% zinc.

Circular oscillation of the beam or the use of a slightly defocused beam is helpful in obtaining sound welds. The most satisfactory technique involves (*a*) the use of integral or tightly fitted backing of the same alloy and (*b*) close control of welding conditions to values that trial welds have shown will either minimize porosity and voids or localize them in an area where they can be machined away later or where they can be tolerated.

Applications. Alloys that have been electron beam welded with good results include casting alloy AZ91C-T6 and wrought alloy AZ80A-T5. Example 479 describes an application in which alloy AZ91C was welded for repair of fatigue cracks in a difficult location.

Welding of Titanium Alloys

All of the commercial alloys of titanium that can be joined by arc welding can also be joined by electron beam welding. Their relative weldability and response to heat cycling in electron beam welding are generally the same as in arc welding, which is discussed in the article on pages 375 to 382 in this volume.

Applicability. The vacuum environment of electron beam welding prevents exposure to the atmospheric contaminants that cause embrittlement of titanium alloys, whereas arc welding processes must use elaborate and costly shielding methods to accomplish this.

Cost studies on welding of Ti-7Al-2Cb-1Ta have shown that direct labor costs for electron beam welding are less than for arc welding, for sections more than 1 in. thick, if a suitably large vacuum chamber is available. A circumferential weld made in a 7-ft-diam, 2⅛-in.-wall cylinder for a deep-submergence vessel took 168 hr for gas metal-arc welding, and approximately 35 min for electron beam welding, including tack welding, penetration welding, repair welding, and a cosmetic pass, but not pumpdown and setup. The detailed cost comparison between electron beam welding and gas metal-arc welding in the Appendix to this article shows little difference for joining ¼-in. thicknesses of Ti-6Al-4V, but a substantial advantage in cost for electron beam welding of 1-in. plate.

Techniques. Filler metal is not ordinarily used, and the work is not preheated. Tack welding, contrary to experience in gas tungsten-arc welding, presents no difficulties in electron beam welding. For optimum results, welding is done in a high vacuum, but medium-vacuum welding is satisfactory in many applications.

Alloy Ti-6Al-4V, the alloy most frequently used in assemblies to be welded, can be electron beam welded in either the annealed or the solution-treated-and-aged condition. For weldments that will be used at elevated temperatures, a preferred process sequence is anneal, weld, solution treat and age. For other service conditions, a process sequence of solution treat, age, and weld gives almost the same strength properties and only slightly lower fracture toughness. This process sequence was used in the application described in the following example.

Example 496. Welding a Heat Treated Ti-6Al-4V Assembly for Close Dimensional Control (Fig. 51)

Design of the complex fuel-injection system of a lunar-module landing engine was based on the use of electron beam welding for joining components of various subassemblies. Electron beam welds provided strength, freedom from distortion, and freedom from burn-through of thin walls.

A typical subassembly was the manifold shown in cross section at the top in Fig. 51. It consisted of two conically shaped parts and was assembled by fitting the upper chambered portion into the solid lower portion, which served as the cover of the combustion chamber. Circular welds A and B sealed the subassembly, providing a conical space between the parts for smooth fuel distribution and cooling of the cover. Other details of fuel and oxygen flow, as well as other welds, have been omitted for simplicity. Enlarged details A and B in Fig. 51 show that the weld at B was the more critical, because of its proximity to 60 drilled holes (0.030 in. from the centerline of the weld joint).

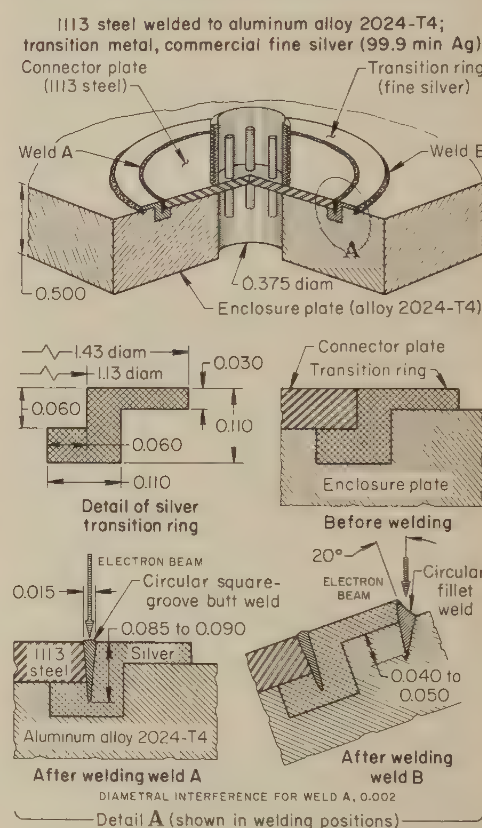
Material for this application was alloy Ti-6Al-4V, solution treated and aged before welding. Postweld heat treatment was not possible because it would have caused excessive distortion, even though several areas were finish machined after welding.

The joints were machined with a 0.002-in. maximum diametral clearance. Also, to facilitate fit, the corner edge of the male part was chamfered, as shown in Fig. 51.

Before assembly, joint surfaces were cleaned by acid pickling and ultrasonic cleaning. Just before welding, the joints were wiped with acetone.

After assembly, the workpiece was clamped in a fixture (not shown) mounted on a turntable in the vacuum chamber. The beam was aligned for weld B while the chamber was being evacuated. Four tack welds were placed at 90° intervals, between holes. The part was moved sidewise, the beam was aligned for weld A, and eight equally spaced tack welds were deposited. Weld A was then completed in one revolution, using beam oscillation and power downslope control. Machine settings and other conditions for these operations are given in the table with Fig. 51.

For the final weld at B, the vacuum was released and the beam realigned. For making this difficult weld, part of the clamping fixture was removed to facilitate the positioning of copper inserts in the holes drilled close to the joint, and to fit a copper ring over the inserts. This precaution was necessary to prevent burn-through in areas where the holes were within 0.030 in. of the joint. A gear change was also required in the turntable drive to maintain a high welding speed on the smaller circle. After pumpdown, the weld was completed in a single pass, using the same oscillation and slope techniques that had been used



Joint type, weld A	Circular butt; rabbeted, self-backing
Joint type, weld B	Circular lap
Weld type:	
Weld A	Square groove
Weld B	Single fillet
Machine capacity	150 kv at 40 ma
Gun type	Triode; fixed
Maximum vacuum	5×10^{-5} torr
Vacuum-chamber size	36 by 23 by 30 in.
Fixtures	Holding clamps; rotating positioner
Welding vacuum	10^{-4} torr
Pumpdown time	5 min
Welding power:	
Weld A	80 kv at 6 ma
Weld B	60 kv at 13 ma
Beam focal point	At work surface
Working distance, heat shield to work	10 in.
Welding speed:	
Weld A	35 ipm (10 rpm)
Weld B	45 ipm (10 rpm)
Beam oscillation	None
Number of passes	One, plus 60° downslope

Fig. 53. Electrical connector plate mounted on the enclosure plate of an electronic-detector package, showing use of a silver transition ring to make a hermetic-seal weld between resulfurized steel and an aluminum alloy (Example 498)

for weld A. However, as shown in the table with Fig. 51, other machine settings were different. Despite the copper chills, it was necessary to use lower amperage for better heat control. Weld penetration was also reduced, as indicated in Fig. 51.

Joining of Dissimilar Metals

The joining of dissimilar metals is an important application of electron beam welding. Many combinations that are difficult to weld or unweldable by other processes can be welded by the electron beam process.*

Indirect Joining. Combinations that cannot be joined directly by electron beam welding can usually be welded by this process when a transition piece or a preplaced filler-metal shim of a metal that is compatible with both work metals is used. This technique was used in Example 498.

Examples of practice in this article that describe direct electron beam welding of dissimilar metals include:

Example	Work metal A	Work metal B
465	8620 steel	Nickel-base GMR-235
478	Invar (64Fe-36Ni)	72Mn-18Cu-10Ni
483	4130 steel	Monel K-500
501	Type 304 stainless	Inconel 600

In each of these examples, some aspects of the welding required special attention because of problems posed by the dissimilarity of the work metals.

In the three examples that follow, the differing properties of the two work metals were the major factors in determining welding procedure.

Example 497. Welding Type 304 Stainless Steel to Oxygen-Free Copper (Fig. 52)

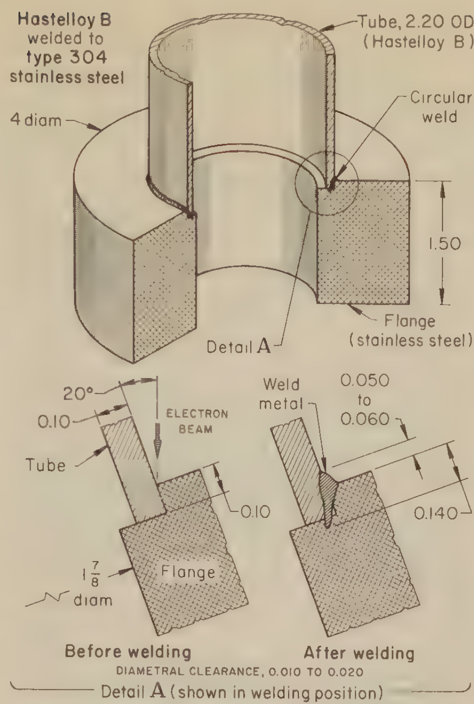
An electron beam welded joint between copper and stainless steel piping of a pressure cooling system was required to be leaktight. The components of the joint (Fig. 52) consisted of a nozzle or flanged tube made of oxygen-free copper and a short length of type 304 stainless steel tubing. Chief considerations in welding the two metals were (*a*) possible expulsion of gas during melting of the copper, and (*b*) the wide difference in properties, such as thermal conductivity, thermal expansion, and melting temperature. Helium mass spectrometry was specified for determining leaktightness of completed welds.

Figure 52 shows the double-rabbeted joint design that was used to provide self-alignment, with the assistance of a simple holding fixture. The beam was aligned to impinge 0.015 in. on the copper side of the joint (section A-A in Fig. 52). Joint penetration was accomplished in a single pass by rotating the assembly under a fixed gun, using the conditions given with Fig. 52. Although gas evolution during welding was not a serious problem, some copper was expelled, resulting in irregularity of the weld surface. A cosmetic pass was made, to smooth the weld, immediately after the principal welding pass by defocusing the beam and manually reducing the beam power, visually observing the effect during the adjustment.

Example 498. Welding of 1113 Steel to Aluminum Alloy 2024-T4, Using a Silver Transition Ring (Fig. 53)

It became necessary to develop a procedure for hermetically sealing an electrical connector housing made of 1113 steel to an enclosure made of aluminum alloy 2024-T4

*See pages 47.40 to 47.43 in Section 3A of "Welding Handbook", 6th Ed., AWS, 1970.



Joint type	Circular corner; rabbeted, self-backing
Weld type	Square groove with fillet
Machine capacity	50 kv at 250 ma
Gun type	Diode; fixed during welding
Vacuum chamber	Steel; 54 by 48 by 48 in.
Fixtures	Part-holding tool for 16 pieces, with individual rotation; table with *x-y* motion
Filler metal	None
Welding power	24 kv at 70 ma
Welding vacuum	5×10^{-5} torr
Pumpdown time	10 min
Working distance	About 4⅛ in.
Beam focal point	On, or slightly above, workpiece junction
Welding speed	60.7 ipm
Number of passes	One, plus 220° downslope
Heat input	1.67 kilojoules per inch
Preheat and postheat	None

Fig. 54. Welding of type 304 stainless steel to Hastelloy B (Example 499)

(Fig. 53). Neither arc welding nor brazing was suitable, as the glass-to-metal seal of the tiny plate and the delicate internal components of the package could not withstand the heat cycling, and electron beam welding was therefore selected.

The metallurgical incompatibility and the differences in thermal expansion, thermal conductivity and melting point of the steel and the aluminum alloy required the use of a transition metal in welding the joint. In addition, the 1113 steel, which had been selected for its free-machining properties, was a resulfurized type (0.24 to 0.33 sulfur), and therefore difficult to weld.

Commercially fine silver (99.9 min silver) was chosen for the transition metal because of its metallurgical compatibility with iron and aluminum, and because it (*a*) was very ductile, malleable and of sufficient strength; (*b*) had a melting point intermediate between aluminum and steel; (*c*) was quickly obtainable; and (*d*) had been used successfully under somewhat similar conditions.

The silver ring, as shown in Fig. 53, was designed to be joined to the steel component by a circular square-groove butt weld (weld A) and to the aluminum alloy component by a circular fillet weld (weld B). The ring was press fitted into a groove machined in the aluminum plate, and the steel plate was press fitted to the silver ring (Fig. 53, detail A). Neither preheat nor postheat was used. Both welds were made on the turntable of a welding positioner constructed for accurate control of position and rotation.

Welding procedures (see the table with Fig. 53) were set up on the basis of trial and error. Under the pressure of time, if a technique or machine setting worked, it was adopted, even though further development held promise of improvement.

For the steel-to-silver butt weld, the most favorable beam alignment was directly on the joint. When the beam was directed on the steel side of the joint, pinholes, which resulted from the sulfur content, made the weld completely unacceptable. When the beam was directed on the silver side, weld appearance was good, but rejections on leak testing were too high. Using the settings shown in the table with Fig. 53 and a beam aligned directly on the joint, the acceptance rate for this weld averaged about 70%. Later tests indicated that an unresulfurized steel would have produced greater joint reliability.

The aluminum-to-silver fillet weld was made by inclining the positioner turntable so that the beam impinged on the root of the joint at an angle of 20°, as shown in Fig. 53, detail A. The fillet weld was satisfactorily produced, with good repeatability.

Weld configurations, as shown in detail A, indicated adequate joint penetration. Where leaks were detected during helium leak testing, the defects were repaired by rewelding. Repeated rewelding, however, sometimes caused cracking of the steel-to-silver weld.

Example 499. Joining Type 304 Stainless Steel to Hastelloy B With Loose Fit-up and Automatic Downslope Control (Fig. 54)

The joint shown in Fig. 54 consisted of a 2.20-in.-OD Hastelloy B tube set into a type 304 stainless steel ring flange. After welding, the joint was required to prove a leak rate of less than 1×10^{-8} cu cm per second by mass-spectrometer testing. Requirements had been met by gas tungsten-arc welding, but because of the availability of an electron beam welding machine for other work (see Example 476) and the desire for increased production, a procedure for electron beam welding was developed.

Cryogenic service conditions determined selection of work metals, and influenced welding procedure. The weldment was part of the equipment used on bulk storage tanks for liquefied gases.

Although interference fits are frequently used to prevent cracking in a restrained circular joint, use of an interference fit in this joint resulted in a hairline crack running circumferentially around the weld. The cracking was ascribed to a number of factors, including large differences in mass, thermal conductivity, and thermal expansion and contraction, and the properties of the weld-metal alloy. It was found that a satisfactory weld could be made if the joint had a diametral clearance of 0.010 to 0.020 in.

Optimum weld contour was obtained by aligning the beam at an angle of 20° to the Hastelloy B tube, with the beam focal point on, or slightly above, the junction of the two members, as shown in Fig. 54. Because macrosections showed that sometimes the electron beam weld did not penetrate to the lower inside corner of the joint, tests were run to compare the strength of such a weld with that of the fillet welds previously made by the gas tungsten-arc process. The results of a reverse-bending fatigue test indicated that the electron beam weld, with partial joint fusion, was stronger than the arc fillet weld.

The electron beam welding machine used in this application was the same as that used in Example 476. A multiple-part rotating fixture was designed to hold and rotate 16 parts individually. Welding conditions used in the operation are given in the table with Fig. 54.

The use of automatic downslope was a critical feature of the welding cycle. Power upslope control was relatively unimportant. At the point of crossover, after one revolution, it was necessary to downslope the power to zero over an additional 220° of revolution to prevent weld cracking.

Figure 54, detail A, shows the weld contour that was usually obtained. Less than 0.5% of the parts were rejected on mass-spectrometer inspection; most rejected parts could be repaired by rewelding.

Electron Beam Welding vs Alternative Processes

The chief advantage of electron beam welding over other welding processes is its ability to make deep, narrow, closely controlled welds in a single pass, with low total heat input and with an extremely short heat-melt-cool cycle (see the sections on Applicability, page 519, and Welding of Complex Assemblies, page 531). Other advantages include high welding speed, ability to make most welds without using filler metal or shielding gas, and applicability to welding in deep, narrow recesses or locations close to other components that are heat-sensitive, or that obstruct access for arc welding.

Major disadvantages of electron beam welding, as pointed out in the section on Applicability, page 519, and in the Appendix to this article, include high equipment cost, high cost of precision joint preparation and precision tooling, and limitations on work size and unit production time when welding is done in a vacuum chamber. Another drawback is that electron beam welds are somewhat more susceptible than arc welds to cold shuts and root voids — particularly welds ½ in. deep or more.

In a survey on selection of welding processes, the major reasons given for choosing electron beam welding in preference to other welding processes were improvement in mechanical properties of joints, reduced distortion, cost reduction, and unique applicability for welding specific assemblies. In more than half of the examples of practice in this article, joint requirements could be met in a practical way only by electron beam welding.

The six examples that follow describe applications for which electron beam welding was selected rather than another fabricating process.

Example 500. Electron Beam vs Gas Tungsten-Arc Welding of D-6ac Missile Cases (Table 4)

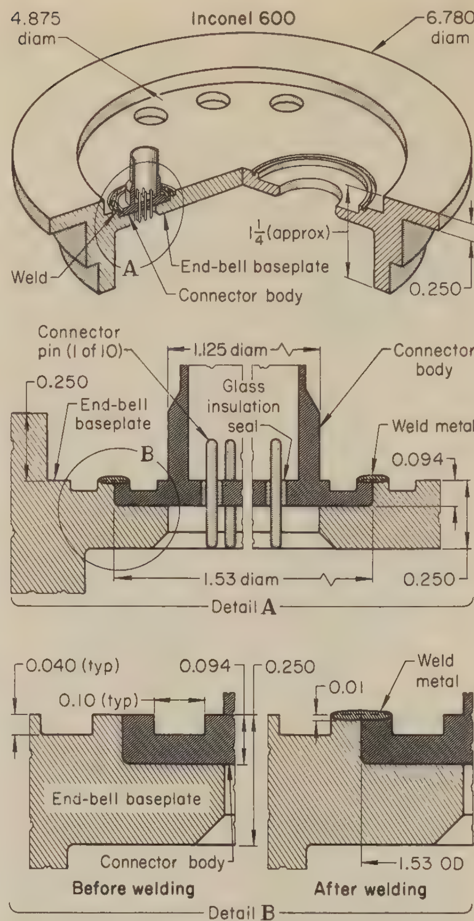
Early experience of one manufacturer in fabricating D-6ac missile cases by automatic gas tungsten-arc welding proved discouraging. The missile cases, which were 6 in. in diameter and 0.040 in. thick, required two girth seams to join the end closures to the shell. Weld porosity was a continuous problem — about 10% of the cases required time-consuming weld repairs to remove defects revealed by radiography. Fractures in hydrostatic burst tests usually started at the weld. Similar tests on cases welded by the electron beam process showed that fractures were not generally associated with the weld.

Pilot runs using electron beam welding showed several advantages. The component parts could be finish machined and then welded, with less than 0.003 in. change in diameter at the weld area. Preheating was not required, welding was faster and was done without pressurized internal backing, and alignment of the square butt joint was achieved by an external hinged ring. After the ring was removed, surface friction maintained alignment until welding was completed.

Only simple end-thrust fixturing was needed. In addition, the appearance of completed welds was sufficiently attractive to eliminate the need for machining. Required quality was ensured by three electron beam penetration passes plus a cosmetic pass. Hardened stock was first used, but was replaced by normalized stock for easier postweld machining.

The success of the electron beam procedure led to a study that projected total costs for the two processes over five years. The results, as shown in Table 4, indicated that electron beam welding was less expensive, based on continuous production welding of the same 6-in. missile cases.

In actual production for a period of six years, the validity of the cost projection was verified, and the electron beam welding procedure showed advantages not included in the original projection. Weld repairs for the removal of defects revealed by radiography were made on less than 5% of the missile cases welded, as compared with a 10% rate with gas tungsten-arc welding. In addition, the repair procedure consisted merely of remelting the weld with the electron beam. The arc weld defects generally had to be ground out and the cavity filled, using filler wire.



Joint type	Circular edge
Weld type	Seal; shallow square groove
Machine capacity	30 kw
Gun type	Pierce; fixed
Filament	Square tantalum ribbon
Vacuum chamber	Stainless clad; 50 by 30 by 42 in.
Vacuum pumps:	
Roughing	140 cfm
Holding	3.5 cfm
Diffusion	10^4 liters per sec at 10^{-4} torr
Fixtures	Three-jaw chuck; holding clamp
Welding power	15 kv at 15 ma
Welding vacuum	10^{-4} torr
Welding speed	35 ipm
Pumpdown time	4 min
Production time	5 min per weld (10 min per assembly)

Electron beam welding, using a heat input of 0.39 kilojoules per inch of weld length, was used instead of gas tungsten-arc welding, to avoid cracks in the welds and nearby glass seals.

Fig. 55. Portion of a welded end-bell assembly for a liquid-metal pump (Example 501)

Example 501. Selection of Electron Beam Instead of Gas Tungsten-Arc Welding To Avoid Heat Damage in Hermetic Sealing of Electrical Components (Fig. 55)

End-bell assemblies for liquid-metal pumps required the welding of two electrical connector bodies to the end-bell baseplate made of heat-resisting alloy Inconel 600. One connector body was made of type 304 stainless steel and contained two connector pins; the other, shown in detail in Fig. 55, was made of Inconel 600 and contained ten connector pins. The metal pins were insulated from connector bodies by glass seals, which were tested for leak rates not to exceed 10^{-8} cu cm per second under 15-psi differential helium pressure, using a mass spectrometer. The welding objective was to obtain completed assemblies having leak rates not exceeding 10^{-7} cu cm per second; hence, weld cracking, weld porosity, and cracking of the glass seals could not be tolerated.

Joint preparation, as shown in Fig. 55, consisted of machining a circular groove near the mating edge of each component part. This type of joint served to (*a*) reduce heat-input requirements by partially isolating the weld, (*b*) reduce heat transfer to the components, and (*c*) avoid high residual stress by yielding slightly under shrinkage stress during cooling.

Welding was originally attempted by using a gas tungsten-arc torch to fuse the joint edges, without a filler-metal addition. These assemblies could not meet leak-rate requirements because small cracks occurred in the welds and the glass seals.

Satisfactory welds were obtained when the procedure was changed to electron beam welding. Higher welding speeds and smaller fusion zones resulted in lower heat input (0.39 kilojoules per inch of weld length). Fixturing was relatively simple, consisting of a holding tool made from a steel bar held by a rotating three-jaw chuck. Because joint penetration of only 10% was required, chill bars were not needed to prevent overheating.

The sequence of operations was as follows. After machining, the parts were degreased, thoroughly cleaned, and dried. One connector body was assembled and fixtured, and the chamber was pumped down. The connector body was tack welded at 0°, 180° and 90°; welding was then started at 270°. After the first connector body was welded, the assembly was removed from the chamber, and the operation was repeated for the second connector body.

Equipment details and welding conditions are given in the table with Fig. 55.

Example 502. Results Obtained by Gas Tungsten-Arc Welding, Furnace Brazing and Electron Beam Welding on Highly Restrained Joints in Beryllium Copper (Fig. 56)

Specifications for a two-piece, copper alloy water jacket permitted the use of gas tungsten-arc welding, furnace brazing or electron beam welding for joining the jacket cover plate to the cast jacket body. As shown at the top of Fig. 56, the cover plate was a flat, annular ring set into the cast body. Joints at the inner and outer periphery, as well as at the eight ribs that served as baffles and reinforcement, were required to be watertight. Water jackets were pressure tested at 50 psi with argon.

Copper alloy 175, high-conductivity beryllium copper (96.9 Cu, 2.5 Co, 0.6 Be), was selected for its combination of thermal conductivity and fatigue strength. The best combination of properties for welding was produced by solution annealing at 1700 F, water quenching, and age hardening at 900 F for 3 to 4 hr. In the age-hardened condition, the material had a tensile strength of 100,000 psi and relative thermal conductivity of 59% (see Table 1 on page 338).

Gas tungsten-arc welding (process A) was initially selected for joining the parts because it had been used on the same ma-

terial in other applications and the equipment was available. Filler metal was copper alloy 172, high-strength beryllium copper, having a nominal composition of 98.1 Cu, 1.9 Be. Joint design called for an 80° V-groove with a 1/16-in. root face for the two circular welds and two 3/8-in. plug welds on each of the eight ribs. The machined and heat treated parts were assembled and preheated to 800 F. Joints were aligned by placing four C-clamps over the ribs and moving the clamps to adjoining ribs as the circular root passes and the plug welds were made. Root passes were made by staggering narrow beads in 1-in.-long increments until all beads were connected. The clamps were removed, and staggered filler passes were made around the two circular joints, and the plug welds were completed. The groove welds were completed with a cover pass. Interpass temperature was maintained at about 800 F by gas torch and welding heat. After welding, the assembly was heated for 3 hr at 800 F.

Although the procedure had been successful for other applications, cracking occurred in the weld and the base metal, because of the high restraint imposed by the two circular welds. Gas tungsten-arc welding with alternating and direct current was tried, without success, and this welding process was abandoned.

Furnace brazing (process B) using a silver alloy filler metal, proved satisfactory, although the procedure was somewhat lengthy and lower base-metal properties had to be accepted, because heat treatment after brazing was impractical. After the parts had been chemically cleaned, surfaces to be joined were silver plated. Brazing strip 0.003 in. thick, of AMS 4772 (AWS BAg-13, having a nominal composition of 54 Ag, 40 Cu, 5 Zn, 1 Ni), was cut to just overlap the areas to be brazed, and the individual pieces, painted with flux, were attached to the casting surface by small resistance spot welds. BAg-13, which has a liquidus of 1575 F and a solidus of 1325 F, was selected for this application after several eutectic, or near eutectic, Ag-Cu-type alloys were tested and rejected.

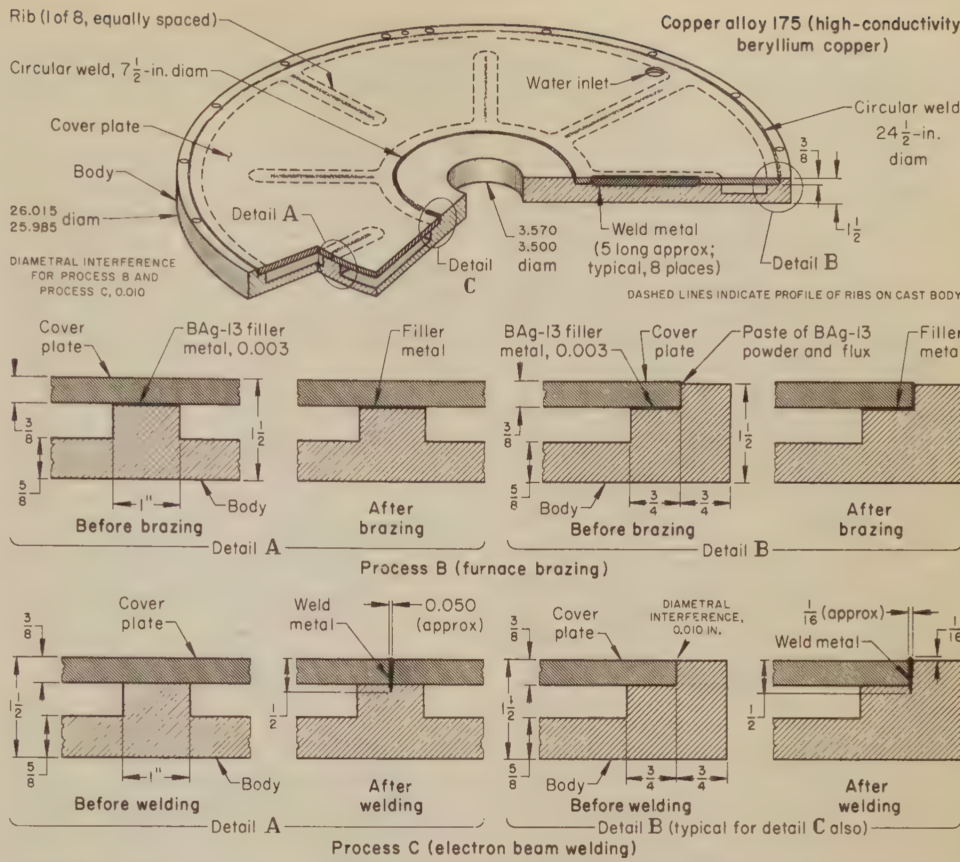
The flat cover plate was then placed on the cast body and brazing powder mixed with flux and water was applied with an eyedropper at the top of the butt joints. Detail views of the joints for process B (furnace brazing), before and after brazing, are shown at the middle in Fig. 56. The circular butt joints were dimensioned for 0.010-in. diametral interference.

The workpieces were loaded into a furnace on a flat graphite plate with the cover side up. Graphite blocks were placed on the cover and weights totaling about 400 lb were stacked on the blocks to hold the joint surfaces in intimate contact.

The assembly was heated to 1700 F in a muffle containing dry hydrogen (dew point, −50 F), was allowed to soak for 20 min, and was then cooled to 1575 F and held for 2 hr at that temperature to obtain further diffusion of the brazing filler metal into the copper alloy. The vertical muffle, with the brazed workpiece, was then removed from the furnace and allowed to cool while being purged with hydrogen. After brazing, the assembly was sand blasted and finish machined.

Electron beam welding (process C) produced the most satisfactory results. Silver plating was not needed, and the maximum heat treated strengths of the finished parts were retained. To prevent cracking in the two circular square-groove butt welds, the cast body and the cover plate were machined to provide a 0.010-in. interference fit, so that the assembled joints were under compressive stress. Joint details for process C are shown at the bottom of Fig. 56.

Welding was done with a general-purpose electron beam welding machine. The welding was done at high vacuum. C-clamps were placed over four ribs, and 1-in.-long tack welds were made at the two butt joints. Four 5-in.-long melt-through (spike) welds were made on the ribs, as shown in Fig. 56. The clamps were moved



Furnace Brazing Conditions

Furnace	Batch type
Atmosphere	Dry hydrogen (−50 F dew point)
Joint preparation	Joint surfaces silver plated
Filler metal	0.003-in.-thick silver alloy strip; also brazing powder mixed with flux and water, AMS 4772 (AWS BAg-13)
Temperature cycle	Heat to 1700 F, soak 20 min; cool to 1575 F, soak 2 hr; remove muffle, cool, H_2 purge

Electron Beam Welding Conditions

Joint types	Circular butt; lap
Weld types	Square groove; melt-through (spike)
Machine capacity	150 kv at 40 ma
Vacuum-chamber size	56 by 56 by 60 in.
Joint preparation	0.010-in. diametral interference
Filler metal	None
Welding power:	
Square-groove welds	150 kv at 50 ma
Melt-through welds	150 kv at 40 ma
Welding vacuum	10^{-4} to 10^{-5} torr
Welding speed:	
Square-groove welds	20 ipm
Melt-through welds	30 ipm
Preheat	None
Postheat	850 F stress-relief and age-hardening treatment

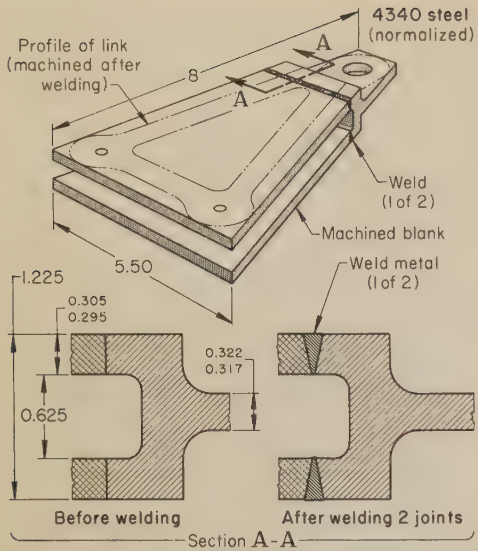
Fig. 56. Water jacket that was satisfactorily joined by furnace brazing (process B) and most successfully by electron beam welding (process C), and sectional views of joints before and after brazing and welding. Gas tungsten-arc welding (process A; not shown) was tried, but could not be used because of weld cracking, caused by high joint restraint. (Example 502)

to the second set of ribs and the welding procedure was repeated. The clamps were then removed and the circular square-groove welds were completed. A postweld heat treatment at 850 F was given to the assembly to age harden the weld area and

Table 4. Five-Year Cost Projection for Electron Beam and Automatic Gas Tungsten-Arc Welding of 6-In.-Diam D-6ac Steel Missile Cases (Example 500)

Item	Electron beam welding	Gas tungsten-arc welding
Production rate, parts per hour	28(a)	8(b)
Amortization cost (5 years):		
Welding machine	$ 85,000	$ 20,000
Pressurized backup tooling	...	12,000
Automatic indexing tooling	15,000	...
Interest at 5%	25,000	8,000
Consumables (5 years):		
Shielding gas, $2.25 per hour	...	10,125
Tungsten electrodes, one per week	...	325
Filaments, one per week	2,500	...
Spare parts, 1% cost per year	5,000	1,600
Power, $0.02 per kilowatt-hour	4,500	865
Labor (10,000 hr):		
Operator, at $7.00 per hour	70,000	70,000
Helper, at $5.00 per hour	50,000	...
Total(c)	$257,000	$122,915
Parts produced (9000 hr)	252,000	72,000
Cost per part	$1.02	$1.71

(a) Includes loading eight parts every 16 min, vacuum pumpdown, welding two circumferential joints, and unloading fixture. (b) Includes loading part in fixture, preheating, welding two circumferential joints, and unloading fixture. (c) Total does not include the cost of reworking rejects.



Joint	Butt
Weld type	Square groove
Machine capacity	150 kv at 40 ma
Gun type	Fixed
Vacuum-chamber size	56 by 56 by 108 in.
Maximum vacuum	10^{-5} torr
Fixture	Clamping jig with 180° rotation
Preheat	None
Welding power	130 kv at 24 ma
Welding vacuum	Less than 10^{-4} torr
Beam focal point	0.250 in. above work surface
Beam oscillation	Circular, 800 hertz
Welding speed	36 ipm
Welding time	4.2 sec per leg
Production rate	1 hr per batch of eight pieces(a)
Postheat	Stress relieve at 950 F for ½ hr; heat treat (see text)

(a) Includes loading, pumpdown, welding and unloading. Monthly production ranged from 40 to 80 pieces.

Fig. 57. Three-piece machined-and-welded link that replaced a one-piece machined link (Example 503)

stress relieve the weldment. The weldment was then air cooled and machined to size.

Data for the furnace brazing and electron beam welding procedures are summarized in the table accompanying Fig. 56. A total of 15 assemblies were joined by electron beam welding.

Example 503. Machining Plus Electron Beam Welding vs Machining for Production of a Steel Link (Fig. 57)

A link, formerly machined from a 1⅜-in.-thick 4340 steel plate, was replaced by an electron beam welded assembly to reduce machining costs. Electron beam welding was chosen instead of arc welding because it consistently provided high joint efficiency and low distortion, especially in welding 4340 steel. The top view in Fig. 57 shows the as-welded blank before machining the final profile, indicated by the phantom line.

With the original one-piece machined link, rejection rate had been high and cutter costs for milling the deep slot between the legs were also high. Machining of the slot was unnecessary when electron beam welding was used. The link blank was made by welding two legs made of ⅜-in. plate and a tongue made of a 1⅜-in.-thick bar, all of normalized 4340 steel. Legs and tongue were finish machined on the top and bottom surfaces to the dimensions shown in Fig. 57. The square-groove butt joints were machine ground, and the parts were then demagnetized. To provide starting and runoff material for welding, the final profile was not machined until after welding was completed.

Before assembly, the parts were vapor degreased and wiped with acetone or methyl ethyl ketone. To permit welding a batch of eight link assemblies during one pumpdown, special clamping jigs were used. Five holes served to position the parts, and a spacer positioned the legs to hold the slot tolerance. The jigged assemblies were mounted in a rotary fixture to permit turning the part over for welding both sides in one pumpdown. Fit-up tolerances, including surface mismatch, were held to 0.005 in. max. Weld traverse was obtained by motion of the holding fixture, while the beam was circularly oscillated at a frequency of 800 hertz.

Details of the machine settings and other welding conditions are given in the table with Fig. 57. After welding, the parts were immediately stress relieved, and then heat treated to a tensile strength of 150,000 to 172,000 psi. A light finish cut was then taken to clean off the weld surface. The welds were examined by magnetic-particle, radiographic and ultrasonic inspection.

Occasionally, it was impossible to machine the top surface of the weld flush, as a result of undercutting. This condition could be detected by visual inspection of the weld surface before removal of the part from the welding chamber, and was corrected by making a cosmetic pass, using a defocused beam. Filler metal was not used.

Changing from all machining to electron beam welding and machining resulted in savings of approximately $50 per piece.

Example 504. Use of Electron Beam Welding To Make Double-Helical Gears With Close Spacing (Fig. 58)

A planetary-gear transmission included five different sizes of double-helical gears of two-piece welded construction. The gears were precision machined and ground from case hardened AMS 6265, a vacuum-melted alloy steel of composition similar to that of 9310. Figure 58 shows a 5.700-in.-OD 38-tooth gear, fabrication of which was typical of the other sizes produced. Two-piece welded construction made it possible to produce double-helical gears of narrow width, low weight and high joint strength. Gear teeth had to be completely finished before assembly, because the closeness of the helixes prevented tool access after assembly. Although mechanical joining could have produced a narrower gear, joint strength would have been inadequate.

Electron beam welding was selected because it was the only process that could produce full joint penetration in a single pass and that had a low enough heat input to avoid distortion. Mating requirements of the helical teeth left extremely little margin for error, and the only machining necessary after welding was reboring of the inside diameter of the gear, finishing of the weld face, and light grinding of the sides of the gear assembly to meet tolerances on over-all width.

In making the double-helical gears, gear halves were machined and case hardened, and tooth surfaces were finish ground to size. The case was ground from the surfaces to be welded. Parts were vapor degreased and rinsed in methyl ethyl ketone.

The gear halves were then assembled in a laboratory, using special gear-measuring equipment. The parts were aligned on a mandrel with the aid of a ¼-in.-square backing-and-alignment ring, which was located as shown in section A-A of Fig. 58. Tooth-to-tooth spacing and lead variation between the two helixes were held within a maximum 0.0002-in. tolerance.

The assembly was loaded into the vacuum chamber, with the mandrel centered on a rotating drive. During pumpdown, the joint was accurately positioned under the fixed electron beam for rotation about the horizontal axis of the gear assembly.

Machine settings for the welding cycle were established by welding test pieces, to ensure ⅛-in. penetration into the backing ring. Maximum combined width of weld and heat-affected zone on each side of the weld was less than 0.125 in. Machine settings and other welding conditions are summarized in the table accompanying Fig. 58. Figure 58 shows details of the joint, backing ring, and completed weld.

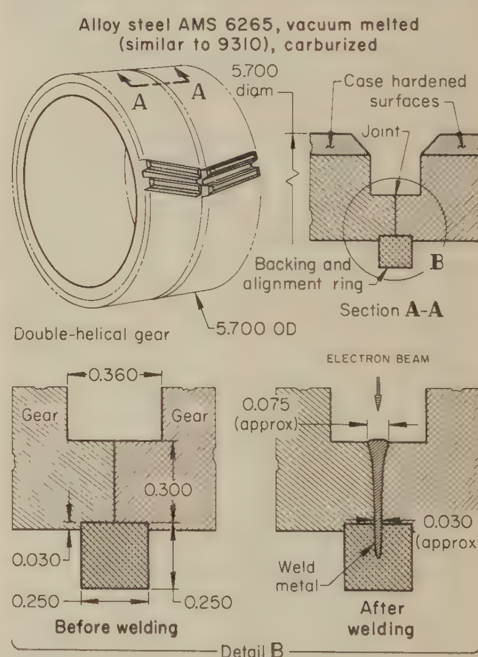
After welding, the entire assembly was heated at 300 F for 3 hr, and the mandrel was removed. The backing ring was removed by machining, and the weld face was machined off for inspection. Dimensions were checked, using the same equipment used for alignment. Welds were examined visually and by magnetic-particle, radiographic or ultrasonic inspection. The bore was finish machined and the sides lightly ground to width tolerance.

The entire production was ten gear assemblies of each of the five sizes, for a total of 50 gear assemblies. To facilitate replacement of parts, gears of any one size had to be interchangeable.

Example 505. Compact Design of Carburized Alloy Steel Aircraft Spur Ring Gear Made Possible by Low Distortion and Low Heat Input of Electron Beam Welding (Fig. 59)

An aircraft spur ring gear, made of AMS 6260 alloy steel (9310), was designed in two pieces for electron beam welding. Two-piece construction overcame design limitations of space and weight, because additional stock was not needed to grind the external gear. The two pieces were machined, carburized, hardened and tempered, and then were electron beam welded without dimensional distortion or damage to hardened surfaces.

Before welding, the joint surfaces were ground for an interference fit. From the standpoint of distortion and heat damage during welding, the critical areas were the two gear surfaces and the internal bearing-race surface, the most critical being the



Joint type	Circumferential butt
Weld type	Square groove, with backing ring
Machine capacity	150 kv at 40 ma
Gun type	Fixed
Vacuum-chamber size	52 by 36 in. by 36 in. high
Maximum vacuum	10^{-6} torr
Fixtures	Aligning and backing ring on mandrel; rotating drive
Welding power	127 kv at 19.7 ma
Welding vacuum:	
During setup	2×10^{-4} torr max
During welding	5×10^{-5} torr
Working distance	6.0 in.
Beam focal point	At surface
Beam spot size	0.015 in.
Welding speed	30 ipm
Preheat	None
Postheat	300 F for 3 hr

Fig. 58. Double-helical gear, showing two-piece construction that was possible only by electron beam welding after the gear teeth had been case hardened and finish ground to size (Example 504)

bearing-race surface, which paralleled the joint and was separated from it by only ⅛ in. Minimum hardness requirements for the race, before and after welding, were Rockwell C 58 and 56, respectively. After welding, the assembly was heated at low temperature and finish ground to size.

For optimum heating efficiency, a narrow, sharply defined beam was required, and therefore the gun was equipped with a special copper anode to minimize the heat effect of fringe electrons in the beam. In addition, a dual-gap focusing coil was installed to minimize beam width. Copper chills, which had been soaked in dry ice and fixtured to the assembly (Fig. 59, top view) about 10 min before welding, served to dissipate heat and to hold critical dimensions. Other features of the procedure, as described below, were based on producing one gear per chamber pumpdown.

After machining, the gear teeth and bearing-race surface were carburized, hardened and tempered to Rockwell C 58. Weld-joint surfaces were machine ground and polished with an abrasive-impregnated rubber stick to obtain a 0.0002-to-0.0008-in. interference fit. Surface film was removed in four steps: (*a*) dip in cold trichlorethylene, (*b*) sonic clean in trichlorethylene at 150 F for 5 min, (*c*) sonic clean in methyl ethyl ketone for 5 min, and (*d*) oven dry at 150 F. Both parts were demagnetized.

Next, the parts were assembled by heating the outer piece to 300 F. When it was cool, the joint was encased in the copper chills and the assembly was mounted on a turntable in the vacuum chamber. Under vacuum, the beam was aligned at low power, using a working distance of 5½ in. Runout was held to 0.002 in. max.

The beam, which had a focal-length range of 2 to 15 in., was adjusted by first obtaining a sharp focus on the joint surface and then reducing the focal length slightly by decreasing the focus current by 0.10 amp. The turntable was set for rotation at 13.6 rpm, causing the 6.23-in. length of joint to traverse the beam at 85 ipm.

Welding was done using the machine settings given in the table with Fig. 59. These settings were previously determined by welding a solid plate to obtain the 0.300-in. minimum joint penetration required. Welding current was adjusted for automatic upslope and downslope. Full power was used for slightly more than one revolution. Sloping the current at start and finish resulted in a complete weld in 1.71 revolutions.

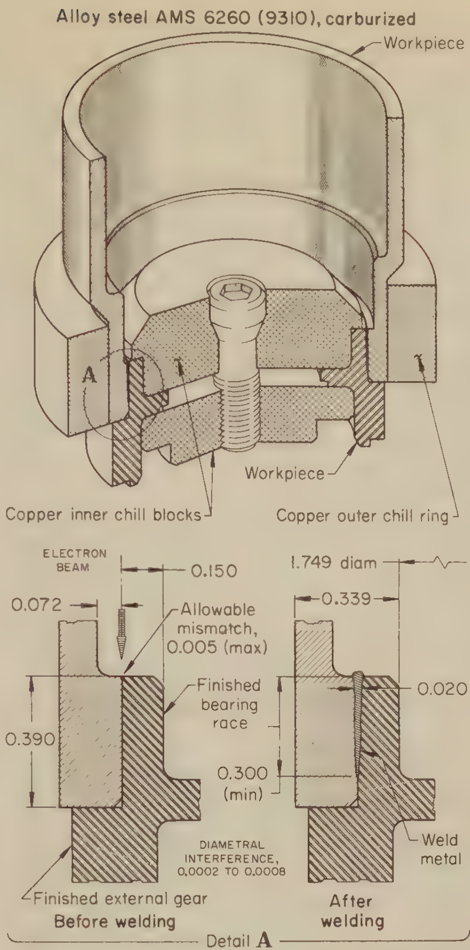
Welded assemblies were heated at 300 F for 2 hr, after which they were finish ground to size. Acceptance criteria were based on two methods of inspection. The first method involved removing two samples from the initial production lot for destructive testing. Parts were required to show 0.300-in. minimum joint penetration, with no cracks. A small amount of porosity was acceptable.

In the second method, nondestructive testing was used. All parts were ultrasonically inspected for cracks and voids, with permanent records being made by print-out of the scan. In service, weld strength was more than adequate.

Safety

Protection must be provided by equipment design and arrangement, and by safety precautions, in electron beam welding and related operations, against the usual hazards of welding and the special hazards of exposure to (*a*) the high voltages involved in generating the electron beam, (*b*) the beam itself, and (*c*) radiation of x-rays produced by impingement of the beam on the work or other materials.

Suitable precautionary measures are described in AWS A6.4, Recommended Safe Practices for Electron Beam Welding, and in ANSI Z49.1, Safety in Welding and Cutting.



Joint type	Circular butt; rabbeted, self-backing
Weld type	Square groove
Machine capacity	60 kv at 500 ma
Gun type	Pierce; triode; fixed vertical position(a)
Special equipment	Copper anode to reduce fringe electrons; dual-gap focus coil for narrow beam
Maximum vacuum	5×10^{-5} torr
Vacuum-chamber size	50 by 30 by 42 in.
Fixtures	Holding clamp, turntable, copper chills
Welding power	58.5 kv at 65 ma
Filament voltage	170 v
Welding vacuum	5×10^{-4} torr
Pumpdown time	5 min
Working distance	5½ in.
Beam focal point	Slightly defocused at surface
Beam spot size	0.020-in. diameter
Power density	12.2 megawatts per square inch
Welding speed	85 ipm
Postheat	300 F for 2 hr
Production rate	7 pieces per hour(b)

(a) Neutral-field cathode was made from steel of high magnetic permeability. Tantalum filament had an estimated life of 100 hr. (b) Includes cleaning, assembly, loading, pumpdown, welding and unloading. Chamber was loaded with one assembly at a time.

Fig. 59. Setup for welding a two-piece spur ring gear without distortion and without heat damage to the hardened internal bearing race ⅛ in. from the weld (Example 505)

APPENDIX

Cost of Electron Beam Welding

The major factors that influence the cost of electron beam welding are high equipment cost, effect of pumpdown time on unit labor cost, and high cost of precise joint preparation and precision tooling.

Equipment Cost. The initial cost of electron beam welding equipment varies considerably, depending on chamber size, type and capacity of vacuum-pumping equipment, beam-power requirements, and degree of complexity and automation of control equipment.

Cost of a general-purpose electron beam welding system, including a relatively simple, powered worktable for translational motion and a lathe-type rotary fixture, is seldom less than $100,000 (see Example 500); cost of more complex systems may be several times this amount, especially with highly refined control and work-handling mechanisms. The absence of a welding chamber in nonvacuum systems is offset, at least in part, by the cost of a shielded work enclosure and high-speed work-handling equipment.

High equipment utilization, preferably in long runs on similar parts, is needed to avoid high amortization charges in unit welding costs.

Pumpdown Time and Labor Cost. A second major factor in electron beam welding cost is the effect of pumpdown time on labor cost per weld (see the discussion of pumpdown on page 521). This effect can be reduced in some applications by using work chambers of minimum size for the assembly being welded, increasing pumping capacity, welding in medium vacuum instead of high vacuum, using dual work chambers or special, vacuum, rotary feed systems with sliding seals, and by other mechanical expedients. Pumpdown time is eliminated in nonvacuum welding, but this method is not applicable for deep, narrow welds.

Cost of Joint Preparation and Tooling. A third major cost factor is the high cost of precise joint preparation and of the precision tooling needed for accurate tracking of the joint by the narrow electron beam.

Favorable Cost Factors. Factors that favor the use of electron beam welding where arc welding is also suitable include high welding speed, deep penetration in a single pass, and the ability to make most welds without using filler metal or shielding gas. In many applications, the localized heat input and extremely rapid thermal cycling of electron beam welding eliminate, or reduce, the cost of related operations such as machining and heat treatment.

Cost Factors in Examples. In Example 466, welding time was reduced, and preheating and two machining operations were eliminated by changing from gas metal-arc to electron beam welding of steam-turbine diaphragms, reducing fabricating time from 17 to 4.75 hr. In Example 503, changing from a one-piece machined part to a three-piece electron beam welded assembly eliminated the milling of a deep slot for a saving of about $50 per piece.

In Example 500, 0.040-in.-wall D-6ac missile cases were fabricated at lower cost by electron beam welding than by gas tungsten-arc welding. The major cost factor was faster production by the electron beam method, which was done at higher welding speed and (unlike the arc method) without preheating. Additional cost advantages not included in the table of cost data for this example were the elimination of

finish machining of the weld face and root, fewer weld repairs, and a less expensive repair procedure for electron beam welding.

Cost of Commercial Welding Services. A survey on prices charged for electron beam welding by job shops has shown charges of from \$25 to \$100 per pumpdown, plus \$0.50 to \$1.50 per weld. The basis for pricing may be a flat rate per hour that includes all services, an hourly rate plus a pumpdown charge, a rate per lineal foot of weld, or variations of these.

Cost Study: Electron Beam vs Gas-Shielded Arc Welding*

Table 5 shows estimated total cost and a detailed cost breakdown developed in a study on the welding of two domed heads on a 24-in.-diam, 36-in.-long cylinder in ¼-in. and 1-in. thicknesses. The analysis was performed for maraging steel, HP 9-4-25 high-strength alloy steel, and Ti-6Al-4V. For 1-in. plate, the analysis showed that the cost of electron beam welding was approximately one-fourth the cost of gas metal-arc welding and one-fifth the cost of gas tungsten-arc welding. For ¼-in. plate, the cost of electron beam welding was slightly less than the cost of arc welding. The two main factors that increased the cost of arc welding the 1-in. plate were the time required to deposit multiple passes, and the cost of the filler wire.

Table 5. Estimated Cost To Weld a 24-In.-Diam Cylinder to an End Dome by Electron Beam, Gas Tungsten-Arc and Gas Metal-Arc Welding (a)

Cost item	¼-in. plate: Electron beam welding	¼-in. plate: Gas tungsten-arc welding	¼-in. plate: Gas metal-arc welding	1-in. plate: Electron beam welding	1-in. plate: Gas tungsten-arc welding	1-in. plate: Gas metal-arc welding
Maraging Steel(b)						
Joint preparation	\$ 7.50	\$10.00	\$10.00	\$20.00	\$ 35.00	\$ 35.00
Set up, weld and clean	11.75	12.25	5.60	12.05	101.40	40.30
Inspection	10.00	10.00	10.00	10.00	20.00	20.00
Total, labor and overhead	\$29.25	\$32.25	\$25.60	\$42.05	\$156.40	\$ 95.30
Tooling	\$ 5.00	\$ 5.00	\$ 5.00	\$ 7.50	\$ 7.50	\$ 7.50
Filler metal	...	5.40	8.40	...	76.20	84.00
Shielding gas	...	2.80	0.53	...	26.35	4.96
Filament	0.14	...	...	0.19	...	...
Vacuum-pump oil	0.34	...	...	0.34	...	...
Power	0.24	0.03	0.03	0.24	0.32	0.24
Total cost	\$34.97	\$45.48	\$39.56	\$50.32	\$266.77	\$192.00
High-Strength Alloy Steel HP 9-4-25(c)						
Joint preparation	\$ 7.50	\$10.00	\$10.00	\$20.00	\$ 35.00	\$ 35.00
Set up, weld and clean	12.10	12.32	8.19	15.88	101.10	63.80
Inspection	10.00	10.00	10.00	10.00	20.00	20.00
Total, labor and overhead	\$29.70	\$32.32	\$28.19	\$45.88	\$156.10	\$118.80
Tooling	\$ 5.00	\$ 5.00	\$ 5.00	\$ 7.50	\$ 7.50	\$ 7.50
Filler metal	...	6.00	8.40	...	75.00	76.20
Shielding gas	...	1.54	0.70	...	13.92	6.65
Filament	0.24	...	...	0.95	...	...
Vacuum-pump oil	0.35	...	...	0.46	...	...
Power	0.25	0.03	0.03	0.32	0.31	0.27
Total cost	\$35.54	\$44.89	\$42.32	\$55.11	\$252.83	\$209.42
Titanium Alloy Ti-6Al-4V						
Joint preparation	\$ 7.50	...	\$10.00	\$20.00	...	\$ 35.00
Set up, weld and clean	12.20	...	5.00	13.52	...	34.90
Inspection	10.00	...	10.00	10.00	...	20.00
Total, labor and overhead	\$29.70	...	\$25.00	\$43.52	...	\$ 89.90
Tooling	\$ 5.00	...	\$ 5.00	\$ 7.50	...	\$ 7.50
Filler metal	...	...	10.70	...	...	107.00
Shielding gas	...	...	0.93	...	...	8.40
Filament	0.24	...	...	0.48	...	...
Vacuum-pump oil	0.35	...	...	0.39	...	...
Power	0.25	...	0.02	0.28	...	0.17
Total cost	\$35.54	...	\$41.65	\$52.17	...	\$212.97

(a) For source of data, see footnote in column 3, this page. (b) Maraging steel containing 18% Ni, 8% Co, 5% Mo. (c) High-strength alloy steel containing 0.25% C, 9% Ni, 4% Co.

Table 6. Assumed Conditions for Electron Beam Welding of a 24-In.-Diam Cylinder to an End Dome for the Cost Analysis Given in Table 5

Condition	Maraging steel ¼ in.	Maraging steel 1 in.	HP 9-4-25 steel ¼ in.	HP 9-4-25 steel 1 in.	Ti-6Al-4V ¼ in.	Ti-6Al-4V 1 in.
Voltage, kv	20	50	20	23.5	22	23
Current, ma	290	320	160	300	140	300
Welding speed, ipm	60	40	30	7.5	30	15
Set up and weld, min	48	49	50	65	50	55

Table 7. Assumed Conditions for Gas Tungsten-Arc and Gas Metal-Arc Welding of a 24-In.-Diam Cylinder to an End Dome for the Cost Analysis Given in Table 5

Condition	Maraging steel: Gas tungsten-arc welding	Maraging steel: Gas metal-arc welding	HP 9-4-25 steel: Gas tungsten-arc welding	HP 9-4-25 steel: Gas metal-arc welding	Ti-6Al-4V Gas metal-arc welding
Current, amp	160	290	230	300	300
Voltage, v	16	29	17	24	35
Welding speed, ipm	4	10	10	15	20
Total gas flow, cfh	60	50	50	50	150
Wire diameter, in.	1/16	1/16	1/16	1/16	1/16
Wire-feed rate, ipm	40	200	66	150	380
Number of passes, total:					
¼-in. plate	2	1	3	2	1
1-in. plate	19	10	28	19	10
Set up, weld and clean, min:					
¼-in. plate	85	39	86	57	35
1-in. plate	706	280	704	444	243

Welding Conditions. Joint preparation assumed for the arc welds was a 90° single-V groove and 1/16-in. root face for the ¼-in. plate, and a 30° single-U groove (¼-in. root radius) and ⅛-in. root face for the 1-in. plate. Groove volume per inch was 0.0352 cu in. and 0.515 cu in., respectively.

Operating conditions assumed for electron beam welding in this cost analysis are given in Table 6. The conditions for the 1-in. material were developed experimentally in this study, and those for the ¼-in. material were based on experimental data obtained in the study and on published data. Lower speeds were used for the HP 9-4-25 steel than for the maraging steel, to avoid porous welds in the HP 9-4-25.

The operating conditions assumed for gas tungsten-arc and gas metal-arc welding are listed in Table 7. They were based on general practice in arc welding these materials and a review of the technical literature.

Equipment Cost. For this analysis, the cost of the electron beam welding machine was estimated to be \$120,000 and to be written off over a ten-year period, at a rate of \$1000 per month, or \$6.20 per hour. The arc welding equipment, for either arc method, was estimated to cost \$12,000 and to be written off in a ten-year period at a rate of \$100 per month, or \$0.62 per hour. The equipment contribution to the cost of welding by either method was based on the total time the equipment was required for setup, making the weld, and cleaning after welding.

Labor and Overhead Costs. Assumed hourly costs of labor and overhead for each operation are:

	Electron beam welding	Arc welding
Welding operator:		
Labor, per hour	\$ 3.50	\$ 3.00
Overhead, per hour	11.20	5.62
Machinists, including overhead, per hour	10.00	10.00
Inspectors, including overhead, per hour	10.00	10.00

The electron beam welding overhead rate was based on a general factory overhead rate of \$5 per hour plus \$6.20 per hour write-off rate; arc welding overhead rate was based on \$5 per hour plus \$0.62 per hour write-off rate.

Cost of Consumables and Tooling. Filler-metal costs were based on prices of \$15 per pound for 1/16-in.-diam Ti-6Al-4V wire and \$6 per pound for the maraging steel and for the HP 9-4-25 steel. The cost of shielding gas was assumed to be \$0.07 per cubic foot.

Tooling cost was estimated as \$2000 for the ¼-in. plate and \$3000 for the 1-in. plate, for both electron beam and arc welding, and was distributed over 200 cylinders (400 welds).

*From M. T. Groves and J. M. Gerken, "Evaluation of Electron Beam Welds in Thick Materials", Technical Report AFML-TR-66-22, Feb 1966, pages 293 to 302

GAS WELDING

CONTENTS

Gas Welding Processes and Their Application to Steel

*By the ASM Committee on Gas Welding of Steel**

GAS WELDING, as it is dealt with in this article, is a manual process in which the metal surfaces to be joined are melted progressively by heat from a gas flame, with or without filler metal, and are caused to flow together and solidify without the application of pressure to the parts being joined. The most important source of heat for gas welding is the oxyacetylene welding torch. Other processes that make use of gas torches are discussed in separate articles in this volume.

The simplest and most frequently used gas welding system consists of compressed-gas cylinders, gas regulators, hoses, and a welding torch. Oxygen and fuel gas are stored in separate cylinders. The gas regulator attached to each cylinder (fuel gas or oxygen) controls the flow of gas from the cylinder to the flexible rubber hose that delivers the gas to a gland attached to the appropriate inlet on the welding torch. At the torch, the gas passes through an inlet control valve and into a mixing chamber; the mixed gases then pass through the welding tip and produce the flame at the exit end of the tip. This equipment can be mounted on and operated from a hand truck, or it can be a stationary installation. Filler metal, when needed, is provided by a welding rod that is melted progressively along with the surfaces to be joined.

The characteristics of the gas welding process discussed in this article are those pertaining mainly to gas welding as used for joining low-carbon steel. Gas welding for joining cast iron, and gas welding for hard facing a variety of metals, are dealt with in separate articles in this volume, and references are made where appropriate.

Capabilities, Advantages and Disadvantages

In gas welding, the welder has considerable control over the temperature of the metal in the weld zone. When the rate of heat input from the flame is properly coordinated with the speed of welding, the size, viscosity and surface tension of the weld puddle can be controlled, permitting the pressure of the flame to be used to aid in positioning and shaping the weld. The welder has control over filler-metal deposition rates, because the sources of heat and of filler metal are separate. Heat can be applied preferentially to the base metal or the filler metal, without removing either from the flame envelope. These capabilities make gas welding best suited for joining thin sheet metal, thin-wall tube, small pipe, and assemblies with poor fit-up, and for smoothing or repairing rough arc welds. Heavy sections can be joined by gas welding, but less economically than by arc welding.

The equipment is versatile, low-cost, self-sufficient, and usually portable. It can be used for preheating, postheating, welding, braze welding, and torch brazing, and it is readily converted to oxygen cutting. The process is well adapted to short production runs, field work, repairs and alterations.

For these reasons, gas welding is used in automotive and aircraft industries, in sheet-metal fabricating plants, and in the fabrication of industrial pipe. Many other industrial plants maintain gas welding equipment on a standby basis for maintenance work.

Metals That Can Be Gas Welded. Most ferrous and nonferrous metals can be gas welded, but an oxy-fuel gas mixture that will give the appropriate flame characteristics — flame temperature, heat-transfer intensity, and composition of flame atmosphere — must be selected. Flame characteristics of various fuel gases and oxy-fuel gas mixtures are discussed in the sections "Oxyacetylene Combustion" (page 569), "Oxy-Hydrogen Combustion" (page 570), and "Combustion of Natural Gas and Propane" (page 570).

Oxyacetylene supplies the heat intensity and flame atmosphere necessary for welding carbon steel, cast iron and other alloys of iron, copper alloys and nickel alloys. Aluminum and zinc alloys are also welded by the oxyacetylene process. Gas welding of steel is done almost exclusively with an oxyacetylene flame. Hydrogen, natural gas, propane and several proprietary processed gases are used as fuel gases in welding lower-melting metals, such as aluminum, magnesium, zinc, lead and some precious metals.

Except for lead, zinc and some precious metals, gas welding of nonferrous metals generally requires fluxes. This also applies to cast iron and stainless steel. In welding carbon steel, the gas flame adequately shields the weld, and no flux is required. Adjustment for correct flame atmosphere is important, but the absence of flux means that there is one less variable to control.

Eighteen examples, presented later in this article (Examples 506 to 523), describe some specific applications of gas welding to steel.

Metals unsuited to gas welding are the refractory metals (columbium, tantalum, molybdenum and tungsten) and the reactive metals, such as titanium and zirconium.

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Major Applications. Gas welding is particularly well-suited to the joining of thin carbon steel sheet, and carbon steel tube and pipe. The ability to control heat input, to avoid burn-through, to change direction quickly, and to bridge large gaps, when welding with this process, is highly advantageous in these applications. Carbon steel sheet, formed in a variety of shapes, often can be welded more economically by gas welding than by other processes. Gas welding is capable of joining small-diameter carbon steel pipe (up to about 3 in. in diameter) with resulting weld quality equal to competitive processes and sometimes with greater economy. Pipe with wall thickness up to ⅜ in. can be welded in a single pass.

Welder Skill. Gas welding requires skill in manipulating the welding rod and the torch flame. In depositing a weld, the welder uses both hands as he works at melting base metal and filler metal, controlling the weld puddle, and obtaining progressive solidification of filler metal of the correct bead shape.

Gases

Oxygen and acetylene are the principal gases used in gas welding. Oxygen supports combustion of the fuel gases. Acetylene supplies both the heat intensity and the atmosphere needed to weld steel. Hydrogen, natural gas, propane and proprietary gases are used only to a limited extent in gas welding.

Oxygen. Only by burning selected fuel gases in high-purity oxygen, in a high-velocity flame, can the high heat-transfer intensity required in gas welding be obtained. Oxygen is supplied for gas welding and cutting at a purity of 99.5% and higher. Because small percentages of contaminants have a noticeable effect on combustion efficiency, oxygen purity should not be below 99.5%. The most common impurities are argon, nitrogen and water vapor. Pure oxygen is so dry that water vapor is promptly absorbed from all forms of moisture, even traces of ice, in hoses and distribution lines.

When the consumption requirement is relatively small, the oxygen is supplied and stored as a compressed gas in standard steel cylinders under an initial pressure of 2200 psi. The most frequently used cylinder (see Fig. 1) has a capacity of 244 scf (standard cubic feet*). The gas is distributed for use under reduced pressure. Equipment for controlling the use of oxygen in gas welding operations is described in the following section on Equipment. When consumption of oxygen is somewhat greater, banks of cylinders are joined through a manifold header to permanent pipeline systems that terminate at various stations of use.

When oxygen consumption exceeds approximately twelve 244-scf cylinders per week, it may be more economical to obtain and store oxygen in liquid form. Liquid oxygen can be supplied in portable cylinders of 3000-scf capacity, or it can be delivered in bulk to a cryogenic tank where it is kept under a pressure of approximately 25 psi. Temperature during storage generally varies from −290 F (at time of delivery) to −180 F. To prevent too-rapid vaporization of the liquid oxygen, storage containers are built with an insulated double wall. To convert liquid oxygen to a gas having the desired rate of flow and the desired pressure, it is fed through a vaporizer. This is essentially a warming coil and pressure regulator. The gas is then piped to points of use.

The distribution and use of oxygen are covered by laws and safety regulations, designed to prevent injury to persons and damage to property. Users should be thoroughly familiar with the rules in the publications cited in the section on Safety, page 578.

*A standard cubic foot (scf) of gas is defined as equivalent to 1 cu ft of gas at 70 F and 1 atm (14.7 psi) pressure. This definition, which is used in the gas industry and some engineering practice, differs from the "standard temperature and pressure" of 0 C (32 F) and 1 atm pressure used in scientific work.

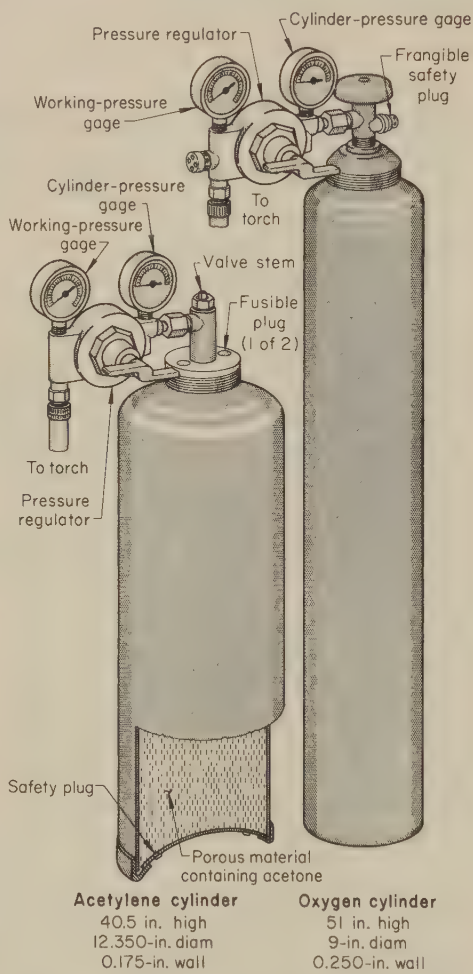


Fig. 1. Portable gas cylinders and regulators used in gas welding. The oxygen cylinder is the standard 244-scf-capacity cylinder, and the acetylene cylinder, the standard 275-scf-capacity cylinder.

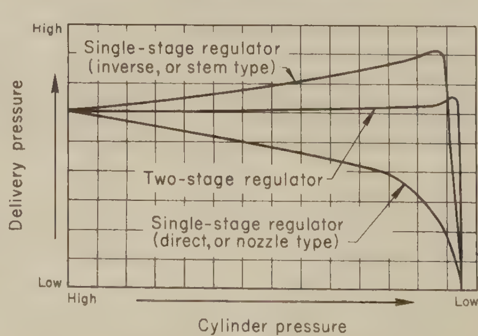


Fig. 2. Typical variation in delivery pressure for three kinds of pressure regulators

Acetylene is a hydrocarbon gas with the chemical formula C_2H_2. (See page 280 in Volume 4 of this Handbook for more information about this gas.)

Acetylene, when under pressure of 29.4 psi and above, is unstable, and a slight shock is likely to cause it to explode, even in the absence of oxygen or air. Therefore, safety rules for the use of acetylene and the handling of acetylene equipment are extremely important. Users and potential users should refer to the publications listed in the section on Safety, page 578.

Acetylene cannot be used safely at pressures greater than 15 psi. Therefore, acetylene generators for on-site gas production are constructed so that the gas will not be given off at pressures much greater than 15 psi. Commercially supplied portable cylinders are specially constructed (see Fig. 1) to store the acetylene under higher pressure. By dissolving the acetylene in liquid acetone, a cylinder such as that shown in Fig. 1 can be used safely to store about 275 scf of acetylene under a pressure of 250 psi. This pressure is reduced to no greater than 15 psi by the regulator (see Fig. 1) before the gas enters the hose or distribution line.

Acetylene cylinders must not be subjected to sudden shock and should be stored well away from any source of heat or sparks. The cylinders must be stored in an upright position to keep the acetone from escaping during use. Acetone will also be drawn off if acetylene is discharged at a rate exceeding 45 cu ft per hour.

Hydrogen is used chiefly for welding lower-melting metals, such as aluminum, magnesium and lead. It is not applicable to the welding of common thicknesses of steel sheet, because it results in a flame temperature that is too low to produce good fusion; it has, however, been used in welding of thin sheet, where its lower combustion intensity (about 60% of that of acetylene) is an advantage. It is used for brazing and, to some extent, for braze welding. Hydrogen is available in compressed-gas cylinders of various sizes.

Natural gas, propane and proprietary gases (each with oxygen) can be used to weld lower-melting metals, but their use in metal joining is usually limited to brazing. These gas mixtures are not applicable to the welding of steel, because when they are burned at temperatures high enough for welding, their flame atmospheres are excessively oxidizing; when ratios of oxygen to fuel gas are reduced to a carburizing condition, flame temperatures are too low.

Equipment

The principal function of gas welding equipment is to supply the oxy-fuel gas mixture to the welding tip at the correct rate of flow, exit velocity, and mixture ratio. The rate of gas flow affects the quantity of metal melted; the pressure and velocity affect the manipulation of the weld puddle and the rate of heating; the ratio of oxygen to

fuel gas determines the flame atmosphere, which must be chemically suited to the metal being welded, and the flame temperature. The following are important elements in a gas welding system: (*a*) gas-storage facilities, (*b*) pressure regulators, (*c*) hoses, (*d*) torch inlet control valves, (*e*) mixing chambers, and (*f*) welding tips.

Gas-Storage Equipment. Compressed-gas cylinders and storage tanks are used as on-site supply sources for gases. They are constructed under regulations of the Interstate Commerce Commission and, to some extent, are further regulated by federal, state and local laws. Cylinders are designed for specific gases and are not generally interchangeable. Sizes and threading of cylinder connections for oxygen, for example, differ from those for acetylene, hydrogen and other gases. It is extremely important that only the appropriate fittings be used for delivery of compressed gas. Users are cautioned not to tamper with valves or safety devices on cylinders.

When portable equipment is not required and gas consumption is large enough, permanent installations are constructed. Gases can be supplied from a variety of bulk-storage vessels, from manifolded gas cylinders, or from gas generators. The gases are then separately piped, at suitable pressures, to terminal stations, where they are drawn off through station regulators and used as in a portable setup.

Storage of oxygen and fuel gases is discussed in the section on Gases, on the facing page.

Pressure regulators deliver gas from a source of supply to the gas hose at a usable pressure and rate of flow. They are designed for specific gases and are not generally interchangeable. In Fig. 1, oxygen and acetylene pressure regulators of a type commonly used in gas welding are shown attached to their respective cylinders and hoses. In operation, gas enters the inlet side of the regulator at cylinder pressure and emerges from the outlet side at the desired working pressure. Regulators are made for various ranges of inlet and outlet pressure. They can be adjusted within their working-pressure range by turning an adjusting screw. This is done after the equipment has been completely assembled and the gas is free to flow from the welding tip. Although some regulators do not have gages and are preset to deliver at a specific and constant pressure, most are equipped with two pressure gages. The one on the outlet side permits the operator to read the adjusted working pressure; the one on the inlet side indicates the pressure in the cylinder.

Two basic kinds of regulators are used in gas welding: single-stage and two-stage. Both kinds are available with either direct or inverse actuation of the valve mechanism. Regulators with direct actuation are known also as positive or nozzle-type regulators; those with inverse actuation, as negative or stem-type. All single-stage regulators reduce cylinder pressure in one step. Not all single-stage regulators are safe to use on high-pressure cylinders. Pipeline regulators, made for lower pressures, must not be used on cylinders.

When adjusted for a desired working pressure, regulators continue to deliver gas, at the pressure shown on the outlet gage, within a fairly narrow range of deviation, as the cylinder pressure drops. The amount and direction of the deviation depend on the design of the regulator. The variation in delivered working pressure as cylinder pressure decreases is shown in Fig. 2 for three types of regulators. Both types of single-stage regulators require occasional adjustment as cylinder pressure drops. The more costly two-stage regulator supplies a more nearly constant working pressure until cylinder pressure nearly equals working pressure. On full oxygen cylinders exposed to low outdoor temperature in winter, two-stage regulators are more reliable than single-stage regulators. Temperature drop of expanding gas is less severe because pressure is reduced in two steps. Also, there is less chance for ice to form and clog regulator passages if water vapor is present.

Hoses. Flexible hoses permit the gas cylinders and regulators to be kept at a safe distance from the working area and allow the welder freedom of movement. They usually range from ⅛ to ½ in. in inside diameter (larger sizes are available for special applications) and are usually available in 25-ft lengths. If hoses are longer than 25 ft, it is sometimes advisable to use either the next-size larger hose or a length of larger-diameter hose with a short length of the normal size to connect to the welding torch to facilitate ease of movement. To ensure that oxygen hoses will be used only for oxygen, and acetylene hoses only for acetylene, oxygen hoses are generally green, with right-hand-threaded fittings; acetylene and other fuel-gas hoses are generally red, with left-hand-threaded fittings. Acetylene-hose fittings are grooved on the outside like the acetylene gland nut shown in Fig. 3 (lower left view).

Welding torches control the operating characteristics of the welding flame and enable manipulation of the flame during welding. The choice of size and style of torch depends on the type of work to be performed. Aircraft welding torches, for instance, are small and light, to permit ease of handling. Most styles of torches permit the attachment of one of several welding tips or a cutting head.

The general construction of an oxyacetylene welding torch is shown schematically in Fig. 3. The principal operating parts are inlet valves, mixing chamber and welding tip (or cutting attachment). By unscrewing the sleeve nut (Fig. 3), the welding tip and mixing-chamber assembly can be removed and replaced by units of different capacity. Torches of this type are used also for oxy-hydrogen welding. Torches for welding with natural gas, propane and proprietary gases may differ in details from the oxyacetylene torch.

Torch inlet valves provide the welder with two important controls. First, the pressure, velocity and flow in cubic feet per hour can be adjusted within the limits set by the pressure regulators and the practical requirements of the welding flame; and second, the ratio of oxygen to fuel gas can be varied. The ability of the oxyacetylene flame to produce the combustion intensity needed for welding, and at the same time to provide a suitable protective atmosphere for the weld metal, is largely a property of the fuel gas, but correct torch settings must be used (see the section on Selection of Tip-Orifice Size and Gas Pressure, next page).

Mixing chambers provide the intimate mixture of oxygen and fuel gas needed for rapid combustion, and also

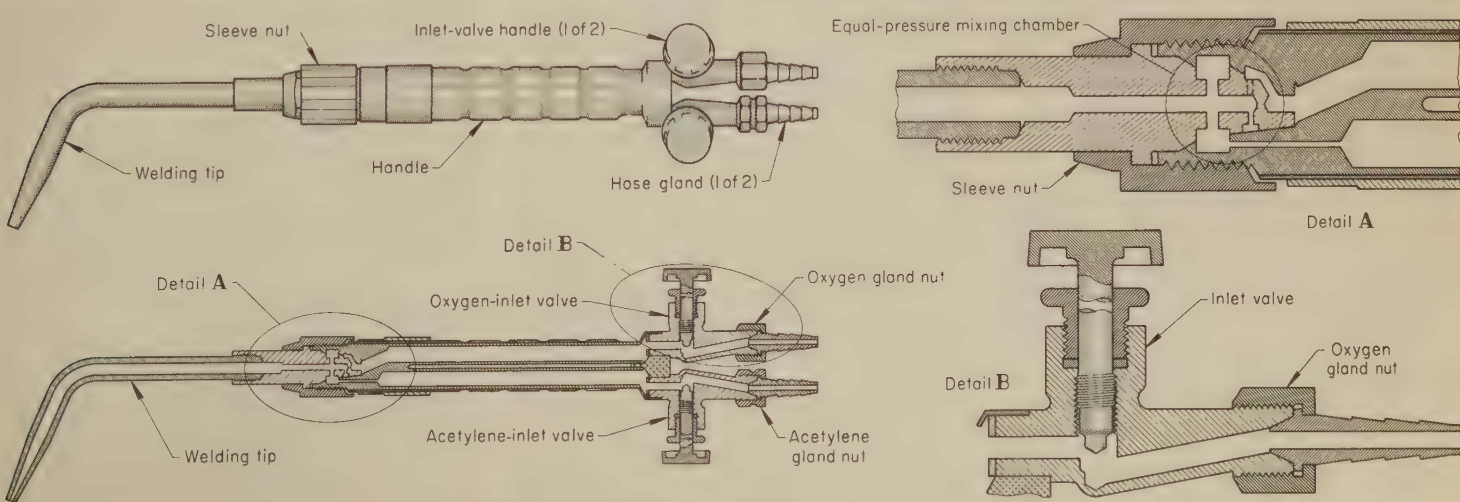


Fig. 3. General construction of an oxyacetylene welding torch

Table 1. Tip-Orifice Sizes, Approximate Gas Pressures, and Acetylene Consumption in Gas Welding of Steel in Thicknesses Ranging From 0.010 to 1 In.(a)

Thickness of steel, in.	Tip-orifice size: Diameter, in.	Tip-orifice size: Drill No.	Gas pressure, psi: Injector torch: Acetylene	Gas pressure, psi: Injector torch: Oxygen	Gas pressure, psi: Equal-pressure torch: Acetylene	Gas pressure, psi: Equal-pressure torch: Oxygen	Acetylene consumption, cfh
0.010	0.0225	74	5	5 to 7	1	1	Up to 1
0.016	0.0280	70	5	7 to 8	1	1	Up to 1
0.019	0.0280	70	5	7 to 10	1	1	Up to 1
1/32	0.0350	65	5	7 to 18	2	2	½ to 2
1/16	0.0465	56	5	8 to 20	3	3	1 to 4
3/32	0.0465 to 0.0550	56 to 54	5	15 to 20	4	4	4 to 6
⅛	0.0550 to 0.0595	54 to 53	5	12 to 24	4	4	6 to 10
3/16	0.0595 to 0.0700	53 to 50	5	16 to 25	5	5	10 to 17
¼	0.0700 to 0.0810	50 to 46	5	20 to 29	6	6	17 to 30
⅜	0.0810 to 0.0860	46 to 44	5	24 to 33	7	7	30 to 45
½	0.0980	40	5	29 to 34	8	8	40 to 60
⅝	0.1285	30	5	30 to 40	9	9	50 to 75
¾	0.1285 to 0.1360	30 to 29	5	30 to 40	10	10	65 to 100
1	0.1540	23	5	30 to 42	12	12	85 to 140

(a) Data are based on one torch manufacturer's recommendations, except for the data on acetylene consumption, which are estimated ranges and include both types of torch.

Table 2. Comparison of Tip-Orifice Diameters and Gas Pressures in Table 1 With Those Used in Production Examples in This Article

Example	Metal thickness, or depth of weld, in.	Tip-orifice diameter, in.: In example	Tip-orifice diameter, in.: In Table 1	Gas pressure, psi: Acetylene: In example	Gas pressure, psi: Acetylene: In Table 1	Gas pressure, psi: Oxygen: In example	Gas pressure, psi: Oxygen: In Table 1
506 (Table 3)	0.048 (18 gage)	0.0675	0.0465(a)	6	3(a)	6	3(a)
507 (Table 3)	0.048 and 0.036 (18 and 20 gage)	0.0510	0.0350(b)	12	2(b)	10	2(b)
508 (Table 3)	0.048 (18 gage)	0.0591	0.0465(a)	14	3(a)	10	3(a)
509 (Table 5)	0.216(c)	0.0595	0.0595 to 0.0700(d)	4	5(d)	4	5(d)
510 (Table 5)	0.280(c)	0.0700	0.0700 to 0.0810(e)	5	5(e)	25	20 to 29(e)
511 (Table 5)	0.322(c)	0.0810	0.0810 to 0.0860(f)	5	5(f)	30	24 to 33(f)
512 (Table 6)	0.050	0.0394	0.0465(a)	12	5(a)	50	8 to 20(a)
513 to 517 (Fig. 19)	0.062(g)	0.0465	0.0465	4	5	28	8 to 20
518 (Fig. 21)	⅜(h)	0.0980	0.0810 to 0.0860	5	5	30	24 to 33
519 (Fig. 22)	3/16(j)	0.0827	0.0595 to 0.0700	7.5	5	15	16 to 25
520 (Fig. 23)	¼(k)	0.0760	0.0700 to 0.0810	9	5	40	20 to 29
521 (Fig. 24)	¼(m)	0.0595	0.0700 to 0.0810	5	5	28	20 to 29
522 (Fig. 25)	¼(n)	0.0465	0.0700 to 0.0810	5	5	17	20 to 29
523 (Table 7)	0.060 (16 gage)	0.0675	0.0465	12	5	45	8 to 20

(a) For welding of 1/16-in. steel; data for 18-gage not given in Table 1. (b) For welding of 1/32-in. steel; data for 18-gage and 20-gage not given in Table 1. (c) Wall thickness of pipe. (d) For welding of 3/16-in. steel; data for 0.216 in. not given in Table 1. (e) For welding of ¼-in.-thick steel; data for 0.280-in. thickness not given in Table 1. (f) For welding of ⅜-in.-thick steel; data for 0.322-in. thickness not given in Table 1. (g) Wall thickness of tubing. (h) Maximum depth of dressed crack repaired by welding. (j) Depth of through hole filled by welding. (k) Maximum depth of joint welded in extending a mandrel. (m) Maximum depth of welded joint. (n) Maximum depth of joint filled by welding.

influence gas flow. In Fig. 3, the mixing chamber is shown as part of an assembly with the welding tip. When the torch is assembled, the mixing chamber is seated on the torch-body gas ducts.

Two general types of mixing chambers are available: the equal-pressure type (also called positive-pressure and medium-pressure) and the injector type. In the equal-pressure type of mixing chamber, the gases are at essentially the same pressure and are mixed by directing the fuel gas into the oxygen stream, both traveling at essentially the same velocity. Detail A in Fig. 3 shows an equal-pressure mixing chamber assembled in position.

In the injector type of mixing chamber, low-pressure fuel gas is aspirated by directing it into a high-velocity stream of oxygen. A nozzle system based on the flow principles of the venturi tube is used. Injector-type torches are useful when fuel gases are supplied at pressures too low to produce a flame of adequate combustion intensity. There is usually no difficulty in supplying oxygen at desired pressure. By varying the design of the injector nozzle, different degrees of aspiration can be obtained. Designs for injector mixing chambers differ considerably in detail; one design is shown in cross section in Fig. 4.

Welding tips are replaceable nozzles that control gas flow by means of the diameter of the exit orifice. Tips of various orifice diameters are usually available for any welding torch. Orifice diameters are identified by drill-size number, by decimal size in inches, or by manufacturer's code number. Because code numbers of different manufacturers do not necessarily correspond, drill sizes or decimals are needed to compare the orifice size of different makes of tips. The performance of tips of equal size, at equal pressure-regulator settings, may differ, however, because of differences in torch and mixing-chamber designs.

Small-diameter tips produce small flames for welding thin sections; large-diameter tips are required for heavier work. Welding tips are made with a smooth bore at the exit end to ensure laminar flow and a uniform flame. The influence of bore configuration on the shape of flame is shown in Fig. 5. When foreign matter, such as carbon, dirt or weld spatter, enters the welding-tip orifice, it must be carefully removed. Specially designed dressing tools (known as tip cleaners) are available for this purpose.

Accessories essential to gas welding include an apparatus wrench made specifically for the several sizes of fittings used to assemble and disassemble the equipment, a friction lighter for igniting the torch, and welder's goggles and gloves.

Welder's goggles are covered by ANSI Standard Z49.1-67, "Safety in Welding and Cutting", which suggests the following lens shade numbers for use in gas welding of steel:

Steel thickness	Shade No.
Up to ⅛ in.	4 or 5
⅛ to ½ in.	5 or 6
Over ½ in.	6 to 8

It is essential for general gas welding that the goggles have side shields.

Selection of Tip-Orifice Size and Gas Pressure

Torch manufacturers supply charts that give tip-orifice size and the approximate gas pressures to be used for welding different thicknesses of metal. Table 1 presents the data from a typical chart showing these relationships. These pressures are approximate and they must be adjusted by the welder to obtain a flame that has the correct ratio of oxygen to fuel gas and other characteristics that may be required for the specific torch or job conditions or are peculiar to his style of work. These adjustments are described in the sections on Flame Adjustment and Oxyacetylene Combustion, below.

Tip size number and drill size are not precise means of comparing tips, because there are significant differences between a tip of the same dimensions when operated under positive pressure and when operated under injector pressure. The only valid basis of comparison is the volume of fuel passing through the tip in a unit of time. Most tips will operate within a range, usually recorded as cubic feet of fuel per hour.

Table 2 compares the tip-orifice diameters and gas pressures used in the production examples described in this article with those shown in Table 1. There are several reasons for the differences: (*a*) the design and performance of regulators, torches, mixing chambers and tips differ from one manufacturer to another; (*b*) a welder will adjust the pressures to suit the particular job conditions; and (*c*) some welders make choices based on personal preference or habit, such as setting the gas regulators at pressures higher than recommended and then throttling down the gases at the torch. It may be claimed that this practice increases welding speed (see Example 512), but it is not a safe practice. It contributes to flashbacks, which are extremely dangerous, and also to backfires. Serious accidents involving flashbacks have occurred when welders have deviated from recommended practice.

Flame Adjustment

Different welding atmospheres and flame temperatures can be produced by varying the relative amounts of oxygen and fuel gas in the gas flowing to the tip of the torch. Usually a welder makes the appropriate adjustments in gas flow on the basis of the appearance of the flame (except in oxy-hydrogen gas welding).

The sequence for setting up a positive-pressure welding outfit is:

1 Individually crack each cylinder valve to blow out foreign matter. Make sure vented gases are safely dispersed. Wipe out cylinder-valve outlet with a clean, lint-free cloth.
2 Attach the oxygen regulator to the oxygen cylinder or manifold.
3 Attach the acetylene (or fuel-gas) regulator to the fuel cylinder or source.
4 Connect the welding hose to the regulators and the welding torch.
5 Individually purge the oxygen line while the acetylene line is closed and the acetylene line while the oxygen line is closed. Vent gases safely.
6 Set the oxygen and fuel-gas regulators to the recommended working pressure with appropriate torch valve open.
7 Open the acetylene (or fuel-gas) inlet valve and light the welding torch, using a spark lighter.
8 Open the oxygen inlet valve and adjust the flame, using both inlet valves.

For injector-type equipment, the sequence and method of setting up will differ from that given above, because high-pressure oxygen aspirates low-pressure acetylene into the torch. There are sufficient differences among brands of equipment so that the user is urged to follow the manufacturer's instructions for exact details in setting up.

The following three sections describe the combustion of acetylene, hydrogen, and natural gas and propane fuel gases with oxygen.

Oxyacetylene Combustion

As the acetylene-oxygen mixture burns from the tip of the welding torch, it displays several zones of combustion, which are clearly recognizable. The over-all chemical equation for the complete combustion of acetylene is:

$$2C_2H_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O$$

Combustion takes place in two stages. The first stage:

$$2C_2H_2 + 2O_2 \rightarrow 4CO + 2H_2$$

uses the oxygen supplied from the cylinder and available in the oxyacetylene mixture, and the reaction can be seen as the small inner cone of the flame. The highest temperature is at the point of this cone. The second stage:

$$4CO + 2H_2 + 3O_2 \rightarrow 4CO_2 + 2H_2O$$

uses the oxygen supplied from the air surrounding the flame. This combustion zone constitutes the outer envelope of the flame.

It may be seen from the above that about two-fifths of the oxygen necessary for the complete combustion of acetylene comes from the oxygen cylinder; the remainder comes from the air. Because of the need for supplemental oxygen from the atmosphere, the acetylene-oxygen flame cannot be used inside of tubes or structures subject to oxygen depletion from gas welding. By varying the relative amounts of acetylene and oxygen in the gas mixture in the torch, a welder can produce different flame atmospheres and temperatures.

The second equation shows that in the first stage, when equal amounts of oxygen and acetylene are burning, neither excess acetylene nor excess oxygen will be present at the high-temperature tip of the inner cone. For this reason, the flame is called neutral, and the gas mixture is often described as an acetylene-to-oxygen ratio of 1 to 1 (or simply as an equal ratio). The condition of the flame is important, because the inner cone is held close to, but not touching, the work metal. If excess oxygen is present, the molten metal will foam and spark and brittle oxides may form in the weld metal. If acetylene is present in sufficient excess (indicated by an acetylene feather greater than about three times the length of the inner cone), carbon will enter the metal; some of the carbon will form carbides and some will burn, causing gas and porosity in the solidified weld metal. In austenitic stainless steels, carbides formed in this manner aggravate susceptibility to intergranular corrosion. In welding steel, the flame should be as nearly neutral as possible, but a perfectly neutral flame is difficult to recognize and it is therefore usual to employ a flame containing a slight excess of acetylene.

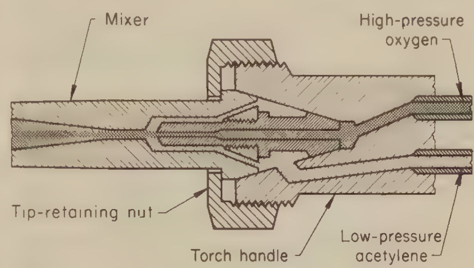


Fig. 4. An injector mixing chamber for a gas welding torch (section taken through joint between welding tip and torch handle)

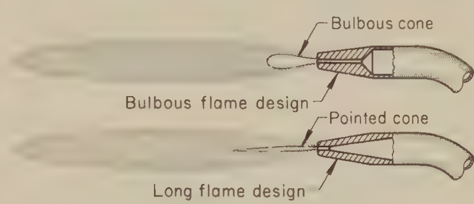


Fig. 5. Shapes of inner cones of oxyacetylene welding flames, produced by welding tips with two different bore configurations. Varying the transition taper produces cone shapes intermediate between those shown.

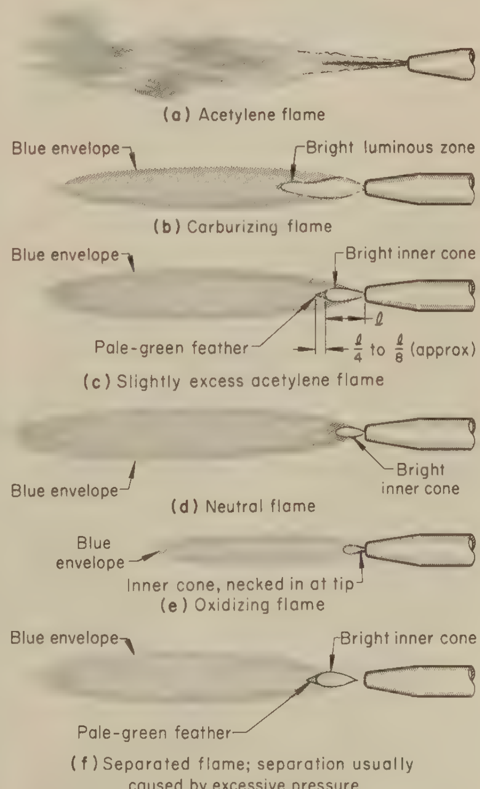


Fig. 6. (a) to (e) *Conditions visible during adjustment of an oxyacetylene flame;* (f) *separated flame caused by excessive pressure*

A neutral flame is obtained by observing the size and color of the combustion zones in the flame as the oxygen-to-acetylene ratio is changed by adjusting the torch inlet valves. Figure 6 shows five typical flame conditions that appear as oxygen flow is increased from zero to excess oxygen, and a separated flame condition that results from excessive gas pressure.

Acetylene Flame. When acetylene alone is burned in air, it produces a flame that varies in color from yellow near the torch tip to orange-red at the extremity, with soot particles floating off into the air. This is not a working flame. This flame is shown in Fig. 6(a).

Carburizing Flame. As the oxygen valve in the torch is progressively opened and the ratio of oxygen to acetylene increases, the flame becomes generally luminous. Then, the luminous portion contracts toward the welding tip, forming a distinct bright zone within a blue outer envelope, as shown in Fig. 6(b). This is a carburizing flame because it has a large excess of acetylene. It is sometimes described as a "soft" flame because it has very little force. It has a relatively low temperature and is used in silver brazing and soldering, and in the welding of lead.

Reducing Flame. As more oxygen is introduced, the bright zone of the flame contracts farther and is seen to consist of two parts: a bright inner cone and a pale-green streamer or "feather" trailing off its end into the blue envelope. The streamer or feather is due to a slight excess of acetylene. It disappears as the oxygen-to-acetylene ratio approaches 1 to 1. In Fig. 6(c), the feather is shown adjusted to about one-quarter the length of the inner cone. For the welding of steel, the length of the feather should be about one-eighth to one-quarter, but never more than one-half, the length of the inner cone. The flame is properly described as a slightly excess acetylene or reducing flame. It should not be called a carburizing flame because it will not carburize the metal, but it will ensure the absence of the oxidizing condition. It is frequently used for welding with low-alloy steel rods. The flame temperature at the tip of the inner cone is about 5300 to 5500 F.

In the neutral flame shown in Fig. 6(d), the oxygen-to-acetylene ratio is 1 to 1 (more accurately, 1.1 to 1) and the temperature at the tip of the inner cone is probably above 5500 F. As pointed out earlier, it is difficult to make the precise adjustment of the inlet valves that results in a neutral flame, particularly in sunlight, because the oxidizing flame is of similar appearance. The neutral flame is ideal for the welding of steel and when

the presence of carbon must be strictly avoided; when the oxidizing condition is unacceptable, as in welding stainless steel, the use of a neutral flame is essential to good results.

An oxidizing flame is shown in Fig. 6(e). The adjustment of the inlet valves for this flame is also difficult, because it cannot be made on the basis of luminosity. The best indication that the oxidizing condition has been obtained is when the flame tends to neck in at the juncture of the inner cone and the tip of the torch. When the flame is adjusted to be extremely oxidizing, it may also produce a hissing sound. An oxidizing flame should never be used in welding steel. Its only use is in welding copper and certain copper-base alloys, and the flame should be just sufficiently rich in oxygen to ensure that a film of oxide slag will form over the weld to provide shielding for the weld puddle. With oxygen-to-acetylene ratios of about 1¾ to 1, flame temperature will exceed 6000 F.

Separated Flame. When gas pressure is too high for the size of the tip used, the flame will separate from the tip (see Fig. 6f) and may even blow out. This is an unusable flame condition and must be avoided. Another cause of this condition is a clogged tip orifice.

Shape of Flame Cone. The design of the welding tip largely determines the shape of the inner cone of the oxyacetylene flame (see Fig. 5); however, as the amount of oxygen used in the gas mixture is increased, the shape of the cone becomes more pointed.

Both bulbous and pointed cones are equally satisfactory and will produce sound welds. The flame with the bulbous inner cone is generally preferred for welding in deep grooves in heavy sections. The flame with the long, pointed inner cone is softer and is preferred for the welding of thin sheet and aircraft assemblies. Some welders prefer the long, pointed inner cone for joining pipe because that shape facilitates penetration and fusion for the root pass in single-V grooves.

Oxy-Hydrogen Combustion

Complete combustion of hydrogen requires an oxygen-to-hydrogen ratio of 1 to 2, as can be seen from the following equation:

$$2H_2 + O_2 \rightarrow 2H_2O$$

This gas mixture produces a strongly oxidizing flame having a temperature of about 5000 F.

It is impossible to obtain a neutral oxy-hydrogen flame by the visual methods of flame adjustment described earlier for the oxyacetylene flame. The oxy-hydrogen flame itself is scarcely visible, and there are no combustion zones such as are typical of the hydrocarbon gases. To avoid an oxidizing flame, the pressure regulators must be set to provide an assured excess of hydrogen. The flame is then reducing but not carburizing, because there is no carbon, and the temperature is several hundred degrees lower than that of the neutral flame. Metering flow-type regulators permit establishing the desired ratio of hydrogen to

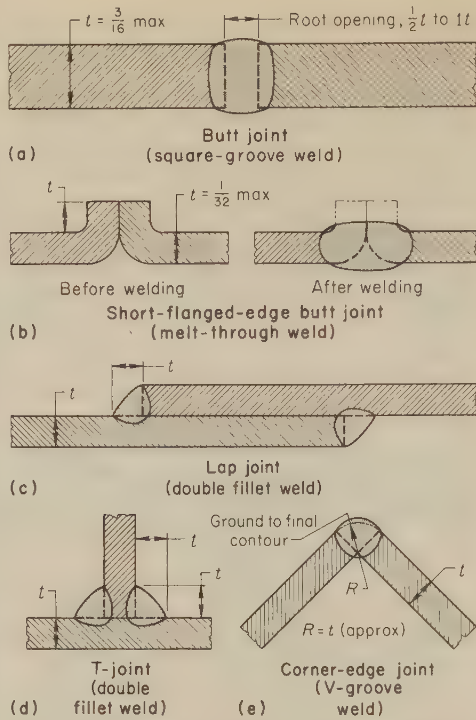


Fig. 7. Typical joints and corresponding single-pass welds used in gas welding of thin sheet

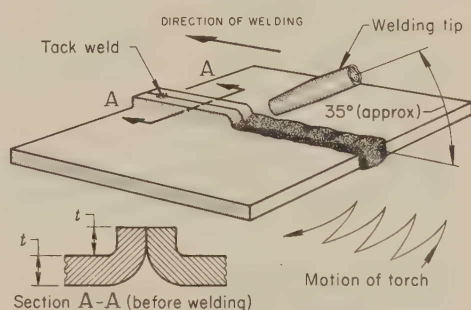


Fig. 8. Gas welding technique for making a short-flanged-edge butt joint in thin sheet (up to about 1/32 in. thick)

oxygen, usually 4 to 1. The oxy-hydrogen flame is useful for welding and brazing aluminum alloys.

Water welding is the misnomer given to an oxy-hydrogen process in which oxygen and hydrogen, generated from water in a small electrolytic cell supplied from the water mains, are produced in the exact quantities needed for complete combustion. The gases are supplied to a torch provided with a welding tip about the size of a hypodermic needle. The flame is oxidizing, but a reducing flame can be obtained by passing the gases over alcohol. The flame produced by recombining the gases from an electrolytic cell is used for joining small parts, such as electronic leads and connections, and in the manufacture of jewelry.

Combustion of Natural Gas and Propane

Complete combustion of natural gas (methane) and propane is shown, respectively, by the following equations:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

When the flame temperature is high enough to weld steel, the flame atmosphere is excessively oxidizing, but when the ratio of oxygen to fuel gas is decreased to produce a carburizing condition, flame temperature is too low.

Welding Rods

Filler metal for gas welding low-carbon steel is available in the form of cold drawn steel rods 36 in. long and 1/16 to ¼ in. in diameter. Welding rods for gas welding other metals are supplied in various lengths, depending on whether they are wrought or cast.

Specifications. Steel welding rods have been standardized in the AWS specification A5.2, "Iron and Steel Gas Welding Rods". The 1969 revision of this specification shows three classifications of welding rods, based on the minimum tensile strength of all-weld-metal and transverse-weld test specimens, as in the table that follows:

AWS classification	Minimum tensile strength, psi	Minimum elong in 4D, %(a)
RG65	67,000(b)	16
RG60	60,000(b)	20
RG45	45,000(c)	...

(a) Elongation in approximately 1 in. (b) All-weld-metal test specimens, 0.252 ± 0.005 in. in diameter; as-welded condition. (c) Tension tests based on transverse-weld test specimens, 2 by ⅜ in. in cross section; as-welded.

The specification covers the chemical composition of the welding rods only to the extent of limiting sulfur and phosphorus to 0.040% max, and aluminum, if present, to 0.02% max. Therefore, welding rods of different manufacturers may vary appreciably in chemical composition. The uses of these three rods are discussed later in this section.

Rods for gas welding of steel have no flux covering and out-of-position welding depends solely on welder skill. Some techniques employed are described in the following section. In the absence of flux coverings, weld-metal properties depend on chemical composition of the welding rod, control of the welding atmosphere, and the techniques used to provide for mixing of base metal and filler metal.

Deposition Techniques. The mechanical properties specified for the RG65, RG60 and RG45 rods are obtained by welding in a neutral to slightly excess acetylene atmosphere. The technique for obtaining this atmosphere is described in the section on Oxyacetylene Combustion in this article.

Forehand and backhand welding techniques can be used in gas welding with rods. Although excessive agitation of the weld puddle is generally undesirable, controlled agitation can be used to aid in the mixing of base metal and filler metal and thereby to secure the desired weld-metal properties.

Weld-Metal Strengthening. The ability to control the properties of the weld by mixing base metal and filler metal means that the choice of welding rod can influence weld strength to a considerable extent, as described in the following: Fully reinforced welds in thin-wall tubes of 4130 welded with an RG45 rod consistently showed tensile strengths of 90,000 to 100,000 psi.

When the welds were made with RG60 rods, the strengths increased to 100,000 to 125,000 psi, and with RG65 rods, strengths as high as 145,000 psi were attained when the joint was heat treated after welding.

Class RG65 welding rods have a low-alloy steel composition and are used for the gas welding of carbon and low-alloy steels that have strengths of 65,000 to 75,000 psi. They are used on sheet, plate, tube and pipe. These rods give the highest strengths in welding 4130, 4340 and 8630 alloy steels when the mixing principle described above is used. The end use has a marked effect on selection of filler metal. For instance, if the base metal was selected to meet a specific corrosion or heat-resisting application, the filler metal should be of similar composition. On the other hand, if a room-temperature mechanical property is the primary requirement, the strength and ductility of the filler metal should be made the basis of selection.

Class RG60 welding rods are probably the most widely used. They are generally of low-alloy steel and are preferred for the gas welding of carbon and low-alloy steels in the tensile-strength range of 50,000 to 65,000 psi. Class RG60 rods are most commonly used for such purposes as welding carbon steel pipes for power plants.

Class RG45 welding rods have a simple low-carbon steel composition. These rods can be used for gas welding of carbon and low-alloy steels.

Fluxes

No flux is used in the gas welding of steel. Fluxes *are* used in the gas welding of cast iron, stainless steel, and most nonferrous metals other than lead, zinc and some precious metals.

Joint Design and Edge Preparation

Joints used in gas welding comprise butt, lap, edge, T and corner joints. Either fillet or groove welds are used, depending on the workpiece and on strength requirements.

Sheet. Five types of joints commonly used for single-pass gas welding of low-carbon steel sheet are shown in Fig. 7. For gas welding, beveling of joint edges is not needed in sheet up to 3/16 in. thick, and if good shearing practice has been followed in trimming sheets to size, no special edge preparation is required. However, edges must be free of rust, dirt, oil, and grease.

Square-groove butt joints (Fig. 7a) can be single-pass welded from one side in sheet up to approximately 3/16 in. thick. Complete-penetration welds, properly made, will develop the same strength in low-carbon steel as the members joined.

Short-Flanged-Edge Butt Joints. For making butt joints in sheet up to about 3/32 in. thick, it is often advantageous to use a short flanged edge (Fig. 7b). The weld is called a melt-through weld because the flanges are melted down to form the butt joint. Filler metal is not required. The oscillating technique for melting down the flanges is shown in Fig. 8. The flanges keep the sheets in flat alignment.

Although the sheet has to undergo a special flanging operation, this joint is practical on long production runs when filler-metal deposition and melt-through are difficult to control. High welding speeds can be attained. Sheet thicknesses are limited to approximately 1/32 in. because short flanges are difficult to bend in heavier material.

In other flanged-edge joints, the weld is deposited on the edges, and the flanges retain their structural identity.

Without appropriate support of the adjacent sheet, long sections of thin material cannot be welded without buckling and distortion. The amount of distortion that results from the expansion during welding and contraction during cooling of the welded sheet-metal section or structure is proportional to the amount of heat applied to the metal as well as to its inherent stiffness and rigidity. Jigs and fixtures are essential to counteract the adverse effects of welding heat. Figure 9(a) shows the elements of a jig commonly used for making butt or flange welds in thin sheet.

Lap and T-joints, as shown in Fig. 7(c) and (d), are single or double fillet welded, depending on strength requirements. A single fillet weld is not recommended if the joint is likely to open under service loads. The amount of overlap in lap joints varies with design requirements and sheet thickness. For double-welded lap joints, a minimum overlap of approximately 1 in. is usually adequate for sheet.

The size of fillet weld (size is defined to mean the leg length of the largest isosceles right triangle that can be inscribed within the fillet-weld cross section) is generally equal to the thickness of the sheet, because this size of weld is easily produced in a single pass and has a good appearance. Lap and T-joints are seldom used where the full strength of joined sections is needed.

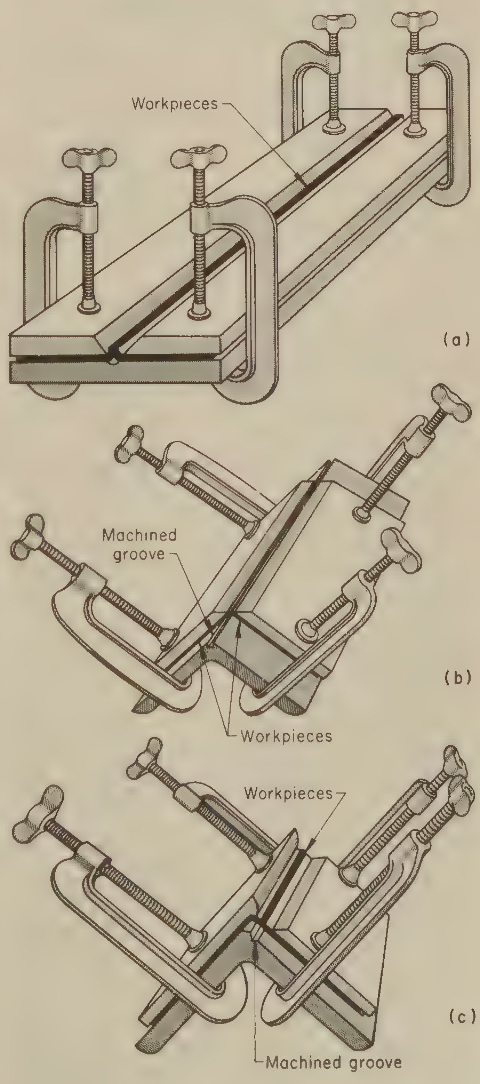


Fig. 9. Jigs used with thin sheet to help maintain flatness and minimize distortion

Both lap and T-joints are somewhat more difficult to weld in thin sections than in thick sections because of the danger of melt-through when a welder attempts to penetrate to the root of the joint.

Corner joints of the type shown in Fig. 7(e) are used in thin material, mainly because of their simplicity and low cost, and because skillful gas welding can produce a weld of good external appearance in a single pass. The usual method employed is to deposit an excess of filler metal in a single pass and then to finish the weld by grinding to a radius approximately equal to the sheet thickness, as shown in Fig. 7(e).

To improve internal appearance and to provide added strength, an internal pass or removable backing is needed. Square corner joints in thin material can be made with good appearance and strength and with little or no distortion by using a jig constructed as shown in Fig. 9(b). A recess is machined or ground in the corner of the backing plate to provide for root reinforcement of the V-groove weld.

When parts with rounded corner joints are designed in thin sheet, consideration should be given to bending rather than joining the corners. Joints next to the corners can be made by butt welding in a jig constructed as shown in Fig. 9(c). Note the use of a recess in the backing member to provide for root reinforcement of the weld.

Plate. Butt, lap, T and corner joints are gas welded in steel plate (3/16 in. and thicker). Butt joints welded from one side only require beveled edges in thicknesses over 3/16 in. However, complete-penetration welds are made in square-groove butt joints up to 5/16 in. thick by single-pass welding from both sides and back gouging the first, or root, pass. Joints are considered to be only partially penetrated when welded from both sides without back gouging the first, or root, pass.

Lap and T-joints can be gas welded in any plate thickness, using single-pass or multiple-pass fillet welds. When these joints are in heavy plate, the size of the fillet welds should be held to a suitable fraction of section thickness to avoid overwelding, which is costly. Corner joints also can be gas welded in any thickness, but in heavy sections this joint design produces an unsatisfactory stress distribution in the weld. One alternative is to extend one of the plates past the other to form a T-joint, which can be double fillet welded; another is to reinforce the corner joint with structural sections.

It should be noted, with respect to heavy plate, that gas welding is at a disadvantage compared to arc welding, because it is slower. Gas welding is not widely used on heavy plate.

Fillet welds have several advantages and disadvantages, compared with groove welds. No edge preparation in the form of chamfering or beveling of joint edges is required. If the weld serves mainly to hold structural members together, or if forces transmitted by the weld are low, fillet welds can be relatively small and economical. If welds are required to develop the full strength, or a high percentage of full strength, of the members joined, fillet welds become more bulky and more costly as section thickness increases.

Groove welds are used in butt joints and can be used in lap, T and corner joints as an alternative to fillet welds. In low-carbon steel, complete-penetration groove welds, properly made, will develop strength equal to the strength of the members joined.

Typical grooves used for gas welding of butt, T and corner joints in steel plate 3⁄16 in. or more thick are shown in Fig. 10. Grooves for gas welding are the same as those for arc welding, except that groove angles are usually larger to permit manipulation of torch and rod, and to provide good access to the root for full penetration.

The V-grooves and single-U groove shown in Fig. 10(a), (b) and (c) are for complete-penetration welds in butt joints. The bevel grooves and J-groove shown in Fig. 10(d), (e) and (f) are similarly used in butt, T and corner joints. Section thickness increases from (a) to (c) and (d) to (f) in Fig. 10. The purpose of changing groove design as section thickness increases is to obtain the least cross-sectional area of weld, and thus to reduce welding cost. The dimensions shown in this figure are typical rather than mandatory; reasonable variations are permissible. A double-U groove and a double-J groove are not shown because they are used for very thick sections, and gas welding of such sections is rare.

The edges of joints intended for groove welds can be prepared by gas cutting, plasma-arc cutting, milling, shaping, planing or turning, depending on the shape and size of the part, and other conditions. Only machine-guided torches should be used when beveling is done by gas cutting.

Pipe. Most pipe welding is done on circumferential butt joints. Wall thicknesses up to about 3⁄8 in., can usually be welded in a single pass. A greater wall thickness requires more than one pass. Grooves must be large enough to permit manipulation of the torch and to facilitate adequate root penetration. The root pass must be made with care and skill to obtain complete penetration and smooth fusion at the inner surface of the pipe. Joints for pipe of up to about 1⅛-in. wall thickness are usually made with single-V grooves. In thicker-wall pipe, the single-U groove may be preferred.

On walls up to and including ⅛ in. thick, a 30° bevel (60° included angle) can be made by grinding the pipe ends. When wall thickness is greater than ⅛ in., the pipe ends are usually beveled to a 37½° angle, which provides a 75° groove angle. These limitations are not mandatory and can be varied somewhat. Smaller grooves are sometimes used by experienced welders.

Bevels can be cut by chipping, grinding, turning or gas cutting. Beveling machines using gas cutting torches or cutting tools are used when large quantities of pipe are involved. Manual gas cutting is used when some form of guided cutting is not available, but manually gas-cut edges are likely to be rough and may have adhering slag. A light grinding operation is often needed to clean the beveled edges and remove gouges before welding.

Elbows, return bends, T's, crosses, Y-branches, reducing sections, end caps and flanges that are to be welded to small-diameter pipe are usually obtained as forged fittings prepared for circumferential butt welding. These fittings have been forged with their ends beveled to an angle of 30° to 37½°, which on fit-up provides welding grooves of 60° to 75° included angle.

When joints must be made in intersecting pipes that are not coaxial, or when pipe diameters differ, the angle of bevel must suit the contour at the intersection.

Thin-Wall Tube. Joints in thin-wall tube vary from simple circumferential butt or lap joints to any configuration resulting from the intersection of a tube with another shape. Whereas pipe is usually beveled, thin-wall tubing (like thin sheet) requires no particular edge preparation. Standard pipe fittings do not generally fit tubes.

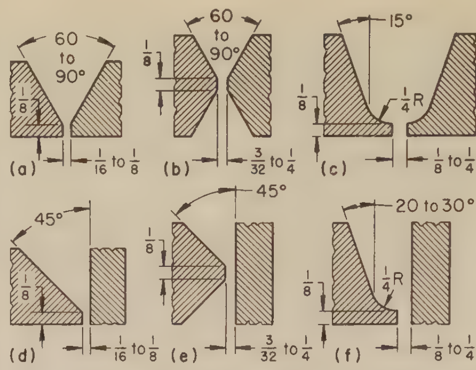


Fig. 10. Typical grooves used in gas welding plate 3⁄16 in. or more thick

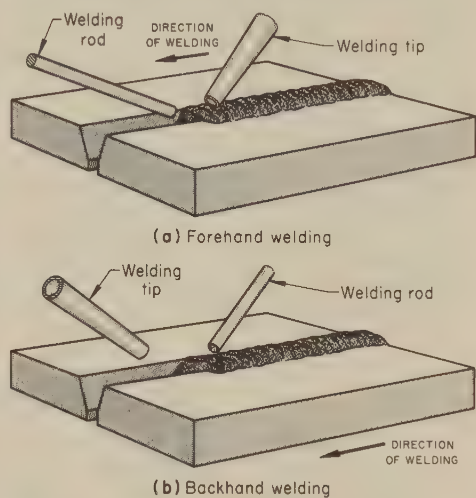


Fig. 11. Two basic techniques for manipulation of the welding tip and the welding rod in gas welding. See text at right for discussion of relative merits of the two.

Several typical joints in thin-wall tube are discussed in Examples 513 to 517, and are shown in Fig. 19.

In repair work and alterations, edge preparation for welding generally involves cutting a V-groove to expose clean metal down to the root of the joint. The groove must be large enough so that there is room for manipulation of the torch and of the welding rod.

In weld repairing of parts that have cracked, the crack should be fully dressed out. Metal can be removed by chipping, grinding, machining, arc-air gouging, or oxyacetylene gouging. For gas welding, oxyacetylene gouging is a convenient method because a cutting torch is generally available and only a special gouging tip is needed.

An advantage in using oxyacetylene gouging for dressing cracks is that the crack remains visible until it is completely removed. Grinding may result in a fine crack being smeared over. Chipping also is likely to cover the crack. The disadvantage in using oxyacetylene gouging is that the heat input may cause the crack to propagate, through differential expansion in the workpiece. The risk is especially great if some of the stresses that caused the crack are still present, or if brittle material such as cast iron is being gouged. Oxyacetylene gouging is not readily accomplished on cast iron.

Cleaning. Cleanness of the joint is a prerequisite for gas welding. Rust, scale, dirt, grease, oil, paint and slag must be removed from the joint areas. The soundness of the weld metal depends in large part on the care exercised in cleaning.

Techniques

Forehand and backhand techniques are used in gas welding, and the usual welding positions (flat, horizontal, vertical and overhead) are employed. Techniques vary to some extent for different joint thicknesses, welding positions and welder preferences.

In forehand welding, illustrated in Fig. 11(a), the flame is pointed away from the completed weld, in the direction of welding, with the torch being held at about 45° to the workpiece. The welding rod is held at an angle of about 40° to the workpiece, with the flame being between the tip of the rod and the weld. The inner cone of the flame is held close to, but not touching, the work. The torch is moved from side to side so that the flame heats the welding rod, the edges to be welded, ahead of the flame, and the weld metal. The rod may be oscillated in a direction counter to the side-to-side movement of the torch. Both the welding-rod tip and the weld puddle should be kept under the shielding influence of the flame.

The forehand technique requires careful manipulation to guard against excessive melting of the base metal, which results in considerable mixing of base metal and filler metal. The influence of the base metal on the properties of the weld metal can be very great.

In backhand welding, illustrated in Fig. 11(b), the flame is pointed toward the completed weld. The tip of the welding rod is held between the flame and the weld, at an angle of about 40° to the workpiece, and the torch, at about 50° to the workpiece. Rod and torch are usually oscillated slightly in opposite directions. Because there is usually less side-to-side movement of the flame and less melting of the joint edges, a backhand weld is more likely to retain the properties of filler metal without alteration by the base metal. There is also less agitation of the weld puddle, better protection of the weld metal by the flame, and slower cooling of the weld than in forehand welding.

Backhand welding is often preferred to forehand welding for joints in metal thick enough to require beveled edges. Smaller grooves can be used because the flame need not be moved around the rod to melt the edges of the groove. Proponents of this technique believe that it saves time, filler metal, oxygen and acetylene. To ensure against cold laps and oxide inclusions at the weld root, the flame should be directed primarily at the heavier and continuous section of base metal when making a fillet weld with the backhand technique, as shown in Fig. 12.

Flat and Horizontal Positions. Gas welding in the flat and horizontal positions presents few problems. However, when root openings must be large because joint thickness is large, the backhand technique is preferred. If the forehand technique is used, it is necessary to work the molten puddle from side to side, as well as forward, with the aid of the flame.

Vertical and Overhead Positions. In vertical and overhead welding, careful control over heat input is needed to keep the viscosity of the weld puddle high enough so that the weld metal does not drip. In addition, the force of the flame must be directed so as to ensure that the weld puddle solidifies in the correct position. The keyholing technique for vertical and overhead welding of thin sheet is described in the next section.

Welding of Thin Sheet

Techniques used in gas welding of thin sheet depend on joint design and welding position, as well as on the style of manipulation used by the welder. Although forehand and backhand techniques can be used for gas welding thin sheet, forehand welding is often preferred because the flame points away from the completed weld and therefore there is less heat buildup and less risk of distortion and melt-through. Proponents of this technique believe also that thin sections can be forehand welded faster in the flat or horizontal position because the flame forces the weld metal to flow in the direction of welding. In Fig. 8, the short-flanged-edge joint is shown being welded with the torch pointed in the forehand direction.

For welding sheet up to ⅛ in. thick in the vertical position, the keyholing technique can be used. This technique requires that the weld be started at the bottom of the joint by building up a shelf, and then progressing upward with a side-to-side motion of the flame as in flat-position welding. When the manipulations of the flame and welding rod are properly coordinated, the effect known as keyholing will occur, as shown in Fig. 13. The same effect can be achieved in overhead welding, but in this position the torch is held perpendicular to the weld puddle and the welding rod is held at about 45° to the weld, leading the flame.

Assemblies of steel sheet less than ⅛ in. thick are often made by gas welding. The risk of melt-through is small because the welder has considerable control over the temperature in the weld zone. However, because of the relatively long welding time involved, gas welding does not permit critical control over total heat input and therefore distortion can occur when long, continuous welds are made in large, flat thin sheets. For this reason, gas welding of thin sections is best done on small parts, where welds can be short, or on sections that have been strengthened by forming. Welding fixtures are often used to prevent distortion and to maintain alignment of joint edges.

The problems arising from difficulties in heat control in joining of thin sections by gas welding are sometimes solved by using other metal-joining processes, such as short-circuiting gas metal-arc welding, pulsed-arc welding, gas tungsten-arc welding, plasma-arc welding, electron beam welding, ultrasonic welding, resistance welding, brazing, and braze welding. These processes are treated in other articles in this volume.

Products that are made by gas welding of thin sheet usually employ material in the thickness range of 0.0239 in. (24 gage) to 0.1196 in. (11 gage). Typical items include truck bodies, furniture, office equipment, utensils, enclosures, and refrigeration equipment. In the three examples that follow, gas welding was selected rather than arc welding to minimize the likelihood of melt-through of the relatively thin (18 and 20-gage) steel sheet used in these applications.

Table 3. Conditions Employed for Gas Welding of Automotive Body Parts From Thin Sheet Steel (Examples 506, 507 and 508)

Condition	Example 506 (Cover assembly)	Example 507 (Truck-body subassembly)	Example 508 (Truck-cab assembly)
Base metal	1008 to 1020, CR	1008 to 1015, CR	1008 to 1015, CR
Thickness, in.	0.048	0.036 to 0.048	0.048
Welding-rod size (in.), and class	1/16, RG60	⅛, RG60	1/16 and ⅛, RG60
Torch	Equal pressure	Equal pressure	Equal pressure
Tip-orifice diameter, in.	0.0675	0.0510	0.0591
Acetylene pressure, psi	6	12	14
Oxygen pressure, psi	6	10	10
Flame adjustment	Neutral	Neutral	Neutral
Joint	Corner	Lap	Lap and butt
Welding position	Vertical	Various	Various
Number of passes	Two per corner	One (7 welds)	One (9 welds)
Weld length per part, in.	28(a)	21	36
Welding time per part, minutes	5 to 6	4	6 (approx)

(a) Four joints, each 3½ in. long, welded on both sides

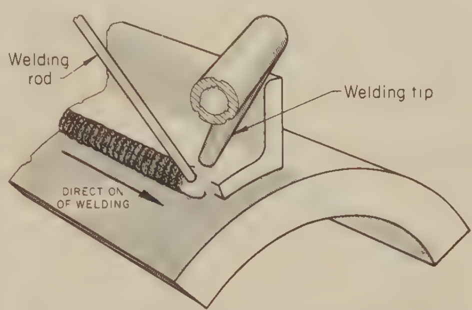


Fig. 12. Technique for preventing cold laps and oxide inclusions in welding unequal sections, by directing the flame at thicker and continuous section

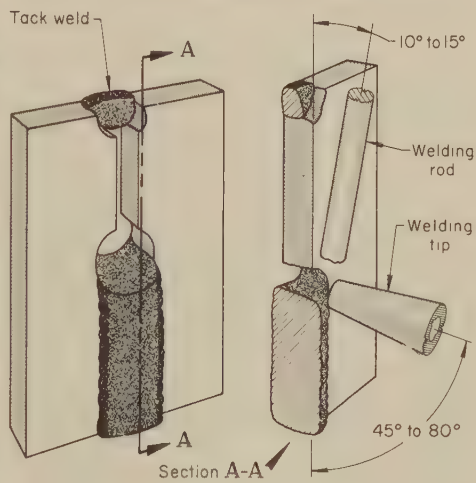


Fig. 13. Keyholing technique used for vertical welding of sheet up to ⅛ in. thick

Examples 506, 507 and 508. Gas Welding of Thin Low-Carbon Steel Sheet

Example 506 — Cover Assembly (Table 3). A cover assembly, in the shape of an open-top box 10 by 12 in. by 3½ in. deep and having a flanged lip, was formed from a single sheet of steel by bending the four sides and the lip. The 3½-in.-deep corner joints were then gas welded inside and out. Specifications called for 18-gage (0.048-in.) 1008 to 1020 steel, cold rolled, with a temper of 3 to 5 (quarter hard to dead soft).

Gas welding was used for closing the four corner joints because experience with arc welding had shown that melt-through was likely to occur. Production schedules depended on speed and reliability. Welding conditions are given in Table 3.

The formed cover assembly was clamped in a welding fixture and welded in the vertical position. Very little warpage occurred and there was no melt-through.

Example 507 — Truck-Body Subassembly (Table 3). A truck-body subassembly required joining a 20-gage (0.036-in.) instrument-panel frame to an 18-gage (0.048-in.) windshield frame. Material specifications called for 1008 to 1015 cold rolled steel of drawing quality, with a temper range of 3 to 5 (quarter hard to dead soft). Seven short lap welds were required to join the parts. A welding fixture held the parts in close alignment so no tack welding was required during fit-up. Various welding positions were used. Because fast, accurate placement of the welds, without melt-through, was required, gas welding was used in preference to arc welding. Welding conditions are shown in Table 3. There was no melt-through, warpage was negligible, and no special problems were encountered.

Example 508 — Truck-Cab Assembly (Table 3). Both lap and butt joints were used for joining sections of a truck-cab assembly. The stampings to be joined were made of 18-gage (0.048-in.) 1008 to 1015 cold rolled steel of drawing quality. The spacing between the parts to be joined was often found to be inconveniently large. Nine welds, made in different positions under good-to-poor fit-up conditions, were required to complete one cab assembly. Average weld length was 4 in.

Attempts had been made to join this assembly manually by shielded metal-arc welding. However, too much melt-through occurred and the welds required cleaning to prepare the surface for a paint finish. Gas welding was found to be fast, for the positions involved, and to produce smooth welds, even where mismatch was encountered. Little finishing was required.

Table 3 gives the operating conditions. Two sizes of welding rod were used, depending on the amount of sheet separation that had occurred during fit-up. Distortion and melt-through were not encountered.

Welding of Pipe

In pipe welding, the weld is usually made from the outside. Care and skill are required to deposit a weld that will

Table 4. Conditions for Single-Pass Gas Welding of Standard and Schedule-40 Pipe (a)

Nominal pipe size, in.	Wall thickness, in.	Length of weld, in.	Welding rod: Size, in.	Welding rod: Lb per weld	Welding time, min	Tip-orifice diam, in.	Gas consumption, cu ft per weld: Acetylene	Gas consumption, cu ft per weld: Oxygen
½	0.109	2.63	3/32	0.10	7	0.0420	0.5	0.5
¾	0.113	3.29	3/32	0.15	8	0.0420	0.7	0.7
1	0.133	4.13	⅛	0.25	9	0.0520	0.9	0.9
1¼	0.140	5.21	⅛	0.30	10	0.0520	1.0	1.0
1½	0.145	5.96	⅛	0.35	11	0.0520	1.5	1.5
2	0.154	7.46	⅛-5/32	0.40	14	0.0520	2.10	2.10
3	0.216	11.00	⅛-5/32	0.50	16	0.0595	3.2	3.2
4	0.237	14.14	⅛-5/32	0.60	20	0.0700	6.0	6.0
5	0.258	17.40	5/32-3/16	0.65	24	0.0700	7.2	7.2
6	0.280	20.81	5/32-3/16	0.90	26	0.0810	11.0	11.0
8	0.322	27.00	5/32-3/16	1.10	30	0.0810	14.90	14.90
10	0.365	33.80	5/32-3/16	1.70	45	0.0810	19.35	19.35

(a) Based on pipe ends beveled to 45° ± 2½° (90° included angle), and welded in the horizontal-rolled position. For welds made in the horizontal-fixed or the vertical position, welding time should be increased approximately 15%. Nominal pipe size and wall thickness are specified in ANSI B36.10-1959. Data are for average production reported by one manufacturer.

penetrate to the inner surface of the pipe without causing objectionable drop-through. Preparation of weld grooves that are large enough to permit manipulation of the torch and to facilitate adequate penetration is discussed in the section on Joint Design and Edge Preparation in this article.

After beveling, the pipe is aligned and tack welded in three or four places to maintain alignment during welding. The pipe ends are usually separated by 1/16 to ⅛ in. to provide a root opening.

Tack welds, whether used to join pipe ends or to support the adjacent edges of a seam to be welded, should be small and have a general appearance as shown in Fig. 14. Such a tack weld will make it possible to blend the tack with the main weld as it is deposited, and thereby to produce a smooth finished weld. Also, a tack weld with a smooth contour makes it easy to obtain fusion where the main weld must be connected with the tack weld.

Welding positions for pipe are determined by the conditions under which the weld can be made. The three basic positions are horizontal rolled, horizontal fixed, and vertical (Fig. 15).

In the horizontal-rolled position (Fig. 15a), the axis of the pipe is essentially horizontal and the pipe is rotated about its axis. For circumferential butt joints, welding is usually done within an angle of about 20° to 45° from the top center of the pipe.

In one frequently used procedure, the pipe is held stationary and the torch is moved to weld a segment. The pipe is rotated to a new position after each segment of the weld has been completed.

A simple fixture for rolling pipe in the field is shown in Fig. 15(b). Depressing the treadle rotates the pipe through a small arc. Then, with the pipe held stationary, the action of the weight causes the treadle to return to its up position. The cycle is repeated a sufficient number of times to rotate the pipe through the desired arc. Other devices can be used to roll the pipe; the simplest approach is to roll the pipe manually on a table or other flat surface, holding it stationary for welding.

The most efficient method of rolling pipe in a plant is by means of power-driven turning rolls. Pipe can also be set on rollers and hand cranked by means of a chain tong.

In the horizontal-fixed position (Fig. 15c), the axis of the pipe is essentially horizontal and the pipe is not rotated. Whether the pipe is supported from below or from above (as shown in Fig. 15c), the supporting members must allow access for welding. For circumferential butt joints, welding can start at the center of either the top or the bottom, and then proceed to the opposite point. The procedure is repeated for the other side of the pipe. Welding actually proceeds from flat to vertical to overhead, or vice versa, depending on whether the start is made at the top or bottom of the joint.

In the vertical position (Fig. 15d), the axis of the pipe is essentially vertical and the pipe may or may not be rotated. With the pipe vertical, a circumferential butt weld is in a horizontal position regardless of whether the pipe is rotated or not.

Rod and Torch Movements. The backhand technique for butt welding pipe in the horizontal-rolled position is illustrated in Fig. 16, with views showing the positions and movements of the welding rod and flame. When the pipe is horizontal and fixed, part of the welding must be done in the vertical position. Figure 17 illustrates how the movement of the end of the welding rod is changed to spread out and widen the weld puddle, although the puddle itself is kept small and shallow in order to control the molten metal.

For butt welding pipe in the vertical position, the positions and movements of the welding rod and flame in the backhand technique shown in Fig. 18 assist in controlling the weld puddle.

Applications. Although gas welding can be used to join pipe of any size and of many different materials, the process is most useful for welding small-diameter carbon steel pipe. Joining carbon steel pipe in diameters up to about 4 in. and in wall thicknesses up to ⅜ in. by gas welding has often proved more economical than by arc welding.

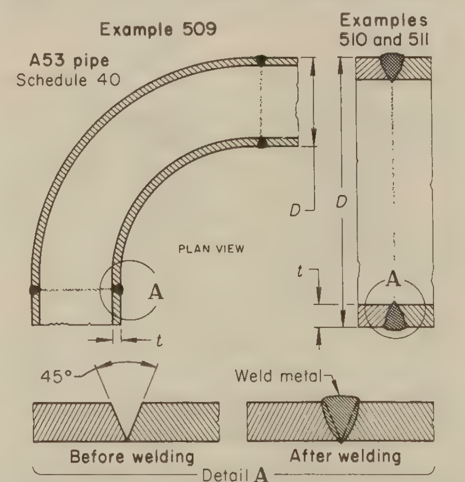
Gas welding offers control over the viscosity of the weld puddle, which is advantageous when pipe is welded in difficult positions. An incidental benefit derives from the fact that gas welding equipment can be easily converted to gas cutting equipment, and a pipe welder who is also an experienced pipe fitter should be capable of cutting almost any type of transition joint that may be required.

Standard-weight (schedule-40) carbon steel pipe up to about 10 in. in diameter can also be gas welded. Although these larger diameters are more efficiently welded by other methods, it is often expedient to use gas welding rather than to change to another process during a piping installation (see Example 511). Data for single-pass gas welding of standard and schedule-40 low-carbon steel pipe, in sizes from ½ to 10 in. and for wall thicknesses from 0.109 to 0.365 in., are given in Table 4.

In the pipe industry as a whole, arc welding plays the dominant role. In some applications, special arc welding techniques have been developed to obtain high joint integrity and greater freedom from human error. However, gas welding applications include pipe systems used in buildings and in various industrial installations for steam and hot-water heating, cooling and air conditioning, gas and air distribution, water distribution, certain types of electrical transmission, and transmis-

Table 5. Conditions Employed for Gas Welding 3-In., 6-In. and 8-In., Schedule-40 Low-Carbon Steel Pipe (ASTM A53) (Examples 509, 510 and 511)

Condition(a)	Example 509	Example 510	Example 511
Pipe size:			
Wall (t), in.	0.216	0.280	0.322
Nominal diam (D), in.	3	6	8
Welding rod:			
Size, in.	3/32	⅛	⅛
Class	RG60	RG60	RG60
Tip-orifice diam, in.	0.0595	0.0700	0.0810
Torch	Equal pressure	Injector	Injector
Gas pressure:			
Acetylene, psi	4	5	5
Oxygen, psi	4	25	30
Flame adjustment	Neutral	Neutral	Neutral



(a) In all of the examples, a circumferential butt joint was welded, weld groove was a 45° V, the horizontal-fixed position was used, and welding was done in a single pass.

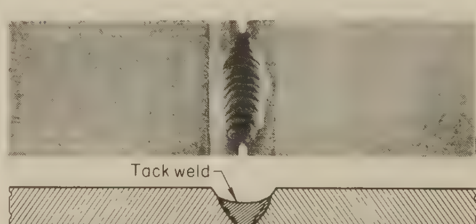


Fig. 14. Preferred contour and relative size of tack weld to obtain successful fusion with main butt weld in pipe

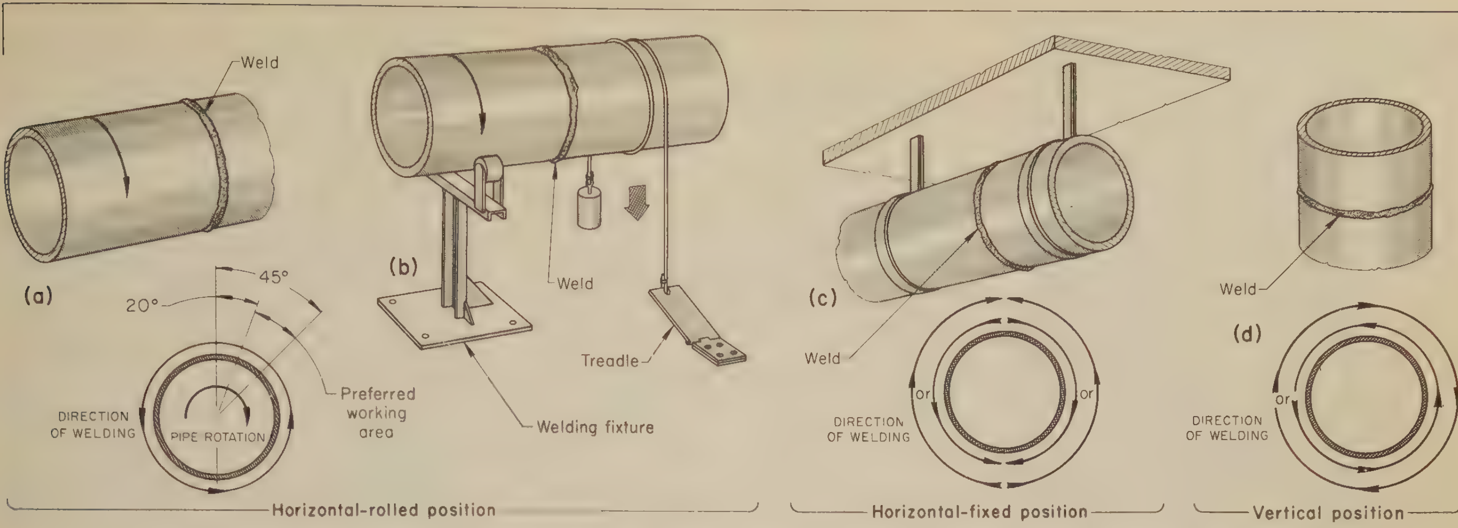


Fig. 15. Three basic positions for welding pipe and a simple turning fixture for welding in the horizontal-rolled position

sion of various commercial fluids. In fact, the welding of small-diameter low-pressure steel pipe is probably the major application of gas welding.

The three examples that follow illustrate welding procedures used for making typical circumferential butt welds in three sizes of low-carbon steel pipe.

Examples 509, 510 and 511. Gas Welding 3-In., 6-In. and 8-In. Schedule-40 Low-Carbon Steel Pipe

Example 509 — 3-In. Pipe (Table 5). The elbow joint shown in Table 5 was typical for a 3-in. local gas-distribution line installed by a piping contractor. It was gas welded using the operating conditions given in Table 5. The welding crew, typical of crews for this work, consisted of experienced gas welders certified for welding pressure pipe. Pipe was cut to size and machine beveled at the site, as required. After alignment and tack welding, the pipe was single-pass gas welded in the horizontal-fixed position. Although operating pressure in the pipeline was 20 psi maximum, the welded joints were tested at approximately 100 psi, with soap and water. No weld defects were found.

Example 510 — 6-In. Pipe (Table 5). A schedule-40 pipeline was welded by a contractor under the conditions shown in Table 5. Where beveling was required, the pipe was machined to a 22½° bevel, which provided a V-groove of 45°. Joints were gas welded in a single pass. Working pressure of the 6-in. pipe was 100 psi, but joints were tested hydrostatically at 400 psi.

Example 511 — 8-In. Pipe (Table 5). A gas company regularly employed a gas welding crew for the installation of small-diameter gas transmission lines. These pipelines sometimes included pipe of larger diameter that was also gas welded, because to change crews and process equipment was not practical. Table 5 shows the joint and gives operating conditions used for welding 8-in.-diam pipe. As with the smaller pipe, the butt joint was welded in a single pass. The V-groove was smaller than that commonly used (see the discussion headed "Pipe" on page 572), but the weld was satisfactory under a hydrostatic-test pressure of 500 psi.

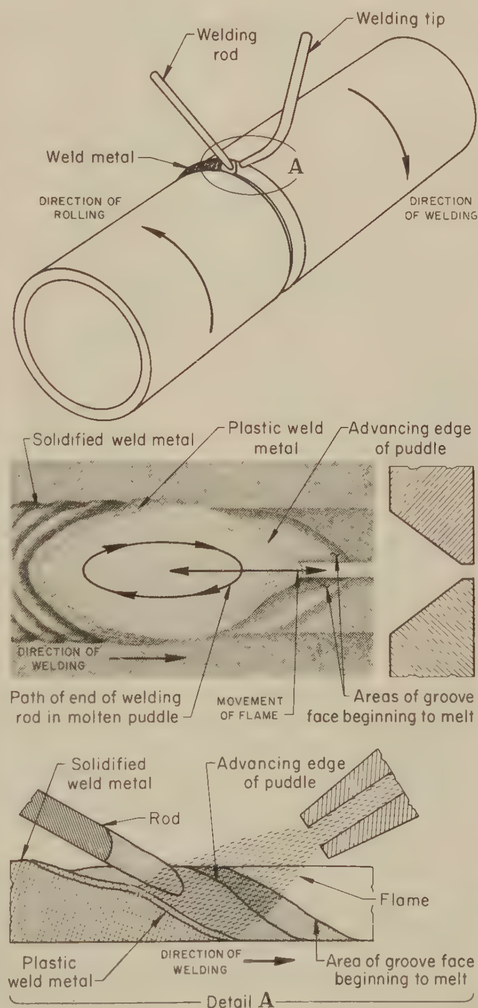


Fig. 16. Positions and movements of welding rod and flame in backhand technique used to butt weld pipe in the horizontal-rolled position

Welding of Thin-Wall Tube

In many respects, the welding of thin-wall tube (⅛-in. wall or less) is similar to the welding of sheet of the same thickness; in other respects, it is similar to the welding of pipe. Gas welding is often preferred for welding thin-wall tube, especially in small diameters, because the equipment is relatively easy to manipulate in confined spaces. Also, there is less risk of overheating and melting through the tube wall. Weld spatter is negligible.

The following examples describe the conditions that determined the selection of gas welding for joining thin-wall, low-carbon steel tube.

Example 512. Gas Welding an Exhaust Assembly for a Truck Engine (Table 6)

Two pieces of 5-in. tube were joined to form an air-vent (exhaust) assembly for a truck engine. Low-carbon steel tube (welded or seamless), with a 0.050-in.-thick wall, was used for this part. A single weld on the outside of a circumferential butt

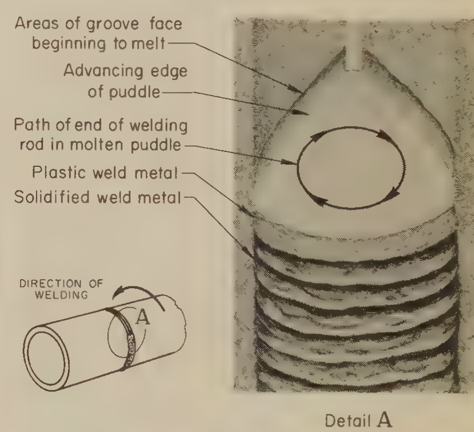


Fig. 17. Positions and movements of welding rod in backhand technique used to butt weld pipe in the horizontal-fixed position

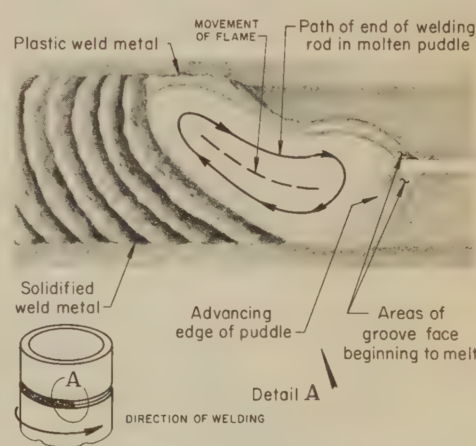
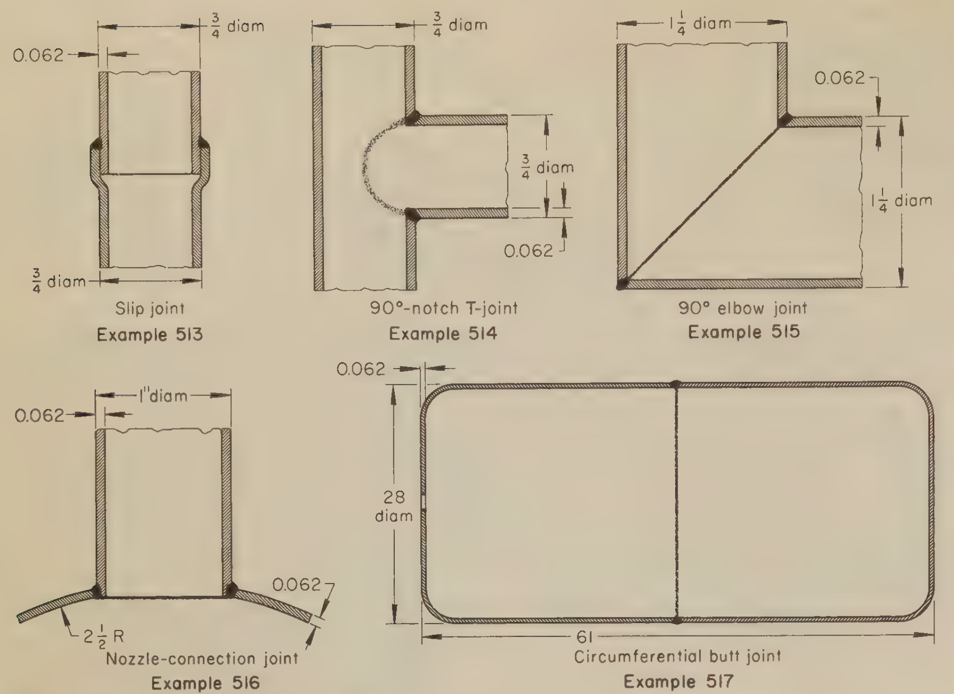


Fig. 18. Positions and movements of welding rod and flame in backhand technique used to butt weld pipe in vertical position



For all joints: Material was low-carbon steel tube with a 0.062-in. wall; welding rod was RG60; tip-orifice diameter was 0.0465 in.; acetylene pressure was 4 psi; oxygen pressure was 28 psi; flame adjustment was neutral; and welding was done in a single pass.
For joints shown as Examples 513, 514 and 515: Pressure employed in hydrostatic testing was 450 psi.

Fig. 19. Typical refrigerator-tubing joints that were gas welded (Examples 513 to 517)

joint was used to join a straight section of tube to an elbow.

In gas welding this assembly, no special joint preparation or welding fixture was used. The two parts were fitted and they were tack welded at four places while resting on a flat steel welding table. One side was welded, the assembly was rolled over, and the other side was welded. Welding conditions are given in Table 6.

Regulator settings for gas pressures were unusually high, especially for oxygen. Because the gas pressures were throttled down by the torch inlet valves to usable proportions, exact torch pressures were not known. However, the equal-flow requirements of the neutral flame, as well as tip size and metal thickness, indicated that actual torch pressures were not far from normal. It was claimed that higher welding speeds were obtained in this manner. Distortion, melting through or service failures have not been encountered with the joint.

Welding conditions were basically the same for the five different joints described in the next five examples. Welded low-carbon steel tube having a 0.062-in.-thick wall was used to convey

Table 6. Conditions Employed for Gas Welding an Exhaust Assembly (Example 512)

Base metal	Low-carbon steel
Wall thickness	0.050 in.
Welding rod	1/16 in., RG60
Torch type	Semi-injector
Tip-orifice diameter	0.0394 in.
Acetylene pressure	12 psi
Oxygen pressure	50 psi(a)
Flame adjustment	Neutral
Joint	Butt
Welding position	Horizontal rolled(b)
Number of passes	One
Weld length	15.7 in.
Welding time	1 min

(a) Regulator setting only (see text). (b) Welded on one side on a table, then turned over and welded on the other side.

liquid refrigerant in gas-operated refrigerators of both home and commercial types. Some of the tubing operated at 250-psi maximum pressure; this tubing was hydrostatically tested at 450 psi. Braze welding was ruled out for these applications because of the risk of galvanic corrosion between copper alloy filler metal and steel tubing. Arc welding was not used because of difficulty in controlling heat input to avoid melt-through. Gas welding avoided these difficulties and also proved more flexible in obtaining access to joints in confined areas.

Examples 513 to 517. Gas Welding Refrigerator Tube

Example 513 — Slip joints (Fig. 19) were made by expanding one end of a piece of tube to receive the mating part and then depositing a single fillet weld around the open joint. This joint was usually made on a moving conveyor line with the tube in the vertical position. Welding conditions are given with Fig. 19.

Example 514 — T-joints (Fig. 19) were cut to size, aligned, tack welded, and welded on a bench as subassemblies. Full-penetration welds were produced. The welding sequence was to complete one side, roll the work over, and then weld the opposite side. The joint detail is shown in Fig. 19, and welding conditions are given in the table with Fig. 19.

Example 515 — Square (90°) elbow joints (Fig. 19) were used to join tube for subassemblies. Welding was done on a moving conveyor line, where it was not always possible to position the joint favorably. Complete-penetration welds were made in 1¼-in.-diam tube in approximately the position shown in Fig. 19. Welding conditions are given with Fig. 19.

Example 516 — Nozzle-connection joints (Fig. 19) were made by welding various diameters of tube to a formed disk of low-carbon steel of the same thickness as the tube. Parts were assembled and welded on a bench. The disk rested on the bench and the tube was positioned on the disk. A single fillet weld was made from the outside.

Example 517 — Circumferential butt joints (Fig. 19) on small storage tanks of 0.062-in.-thick low-carbon steel were gas welded using small turning rolls to rotate the work. A single, full-penetration butt weld was deposited from the outside. Tube connections were located and welded in place in a later operation. Welding conditions are given with Fig. 19. The joint was tested later for tightness at a low static head. The tanks were processed together with the tubing. The type and thickness of material and welding procedure were the same as in the four preceding examples.

Repairs and Alterations

Gas welding is frequently used for repairs and alterations because the equipment is portable, welding can be done in all positions, and acetylene and oxygen are readily available. Also, gas cutting, braze welding, brazing or flame heating are often needed and

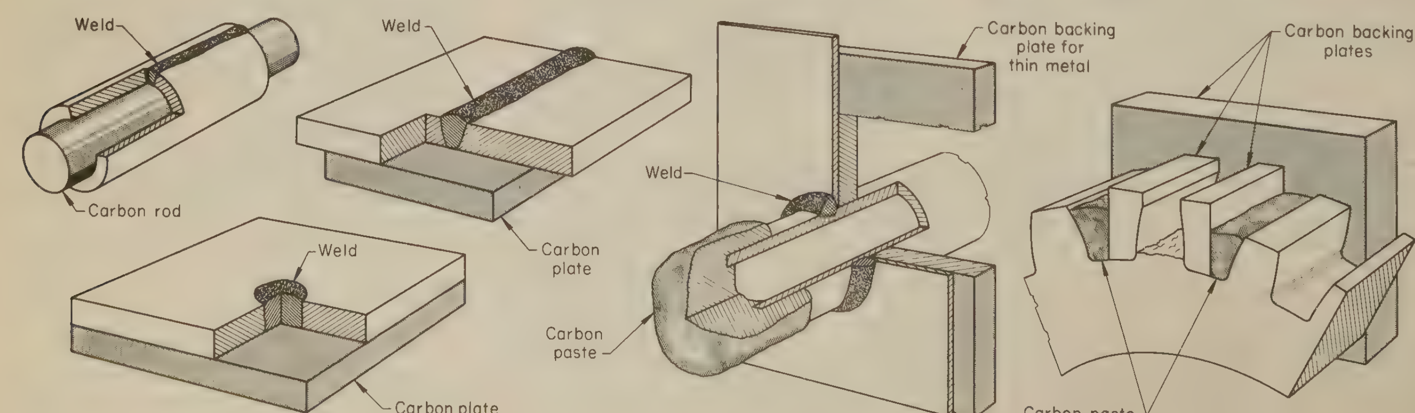


Fig. 20. Carbon backing and support to expedite repair welding of surfaces and contours

the same personnel, equipment, and gases required for these operations can be used for gas welding.

On many repair welding jobs, sections that must be rebuilt to specific contours or dimensions require backing to support the weld metal. Carbon paste, which can be molded, or carbon plate, which can be easily machined, can be used for backing, as shown in Fig. 20. To avoid carbon pickup, copper or a thick steel plate can be used, if care is taken to prevent welding of the backing to the part.

Edge preparation for repair work and alterations is described on page 572 in this article. To ensure complete crack removal, liquid-penetrant or magnetic-particle testing can be used. Parts under stress must not be cut or welded. Repairing a tank can be dangerous (see AWS A6.0-65, Safe Practices for Welding and Cutting Containers That Have Held Combustibles).

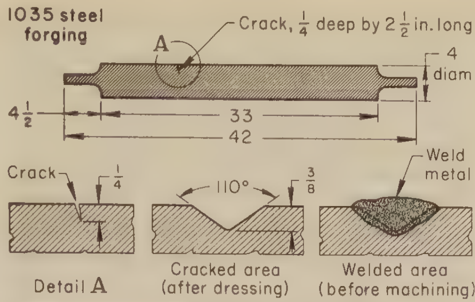
In many applications of repair welding, elaborate precautions are not needed. The following example describes the repair of a cracked steel roll.

Example 518. Use of Gas Welding for Repairing a Cracked Roll (Fig. 21)

A crack approximately ¼ in. deep and 2½ in. long developed in a roll 4 in. in diameter by 42 in. long. The roll (Fig. 21) was a 1035 steel forging.

To avoid purchasing a new forging and undergoing the expense of machining the roll surface, splines and keyways, the crack was repaired by welding. Gas welding was selected because it produced a lower temperature gradient at the weld than arc welding and because the gas torch provided a convenient source of heat for local preheating and for postweld heat treating.

First, the crack was dressed out by gas gouging to sound metal, to provide a V-groove with an included angle of about 110°. The area around the groove was preheated to 400 F and then weld metal was deposited. After welding, the joint area was wrapped in asbestos and allowed to cool to room temperature. Before the weld was machined, it and the heat-affected zone were partly stress relieved for ½ hr at 1050 F, by use of a gas torch. Temperature-indicating crayons were used to establish preheat and stress-relief temperatures. Operating conditions are summarized in the table accompanying Fig. 21.



Welding rod	3⁄32 in., RG65
Torch	Injector type
Tip-orifice diameter	0.0980 in.
Acetylene pressure	5 psi
Oxygen pressure	30 psi
Flame adjustment	Neutral
Welding position	Flat
Preheat and interpass temperature	400 F
Stress relief (partial)	1050 F, ½ hr

Fig. 21. Roll in which a small crack was repaired by gas welding (Example 518)

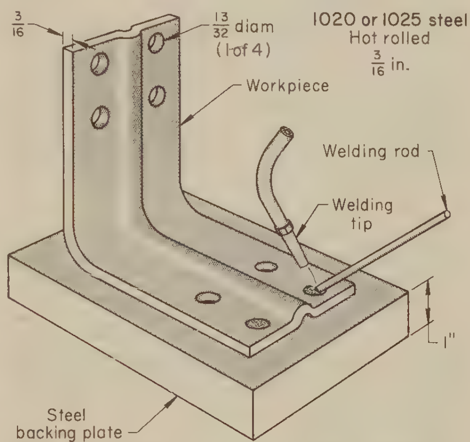
When gas welding is used to correct production parts that would be rejected because of a small error or defect in manufacture, good judgment must be used to determine if the salvaged part, after welding, will be as good as a new part for the service. Some fabricating codes identify the defects that may be rectified by welding and define the standards for repair. Rectification may include correction of defects, building up of undersize parts, and filling in of drilled holes.

In the following example, gas welding provided a simple means of salvaging a large number of parts, without detrimental effects on serviceability.

Example 519. Salvaging Incorrectly Drilled Brackets (Fig. 22)

When a large number of brackets were incorrectly drilled, the manufacturer decided to salvage them by welding the incorrect holes and redrilling. The brackets, as shown in Fig. 22, had two 13⁄32-in.-diam holes at each end; the holes had been drilled too close to the edges. The brackets had been formed of 1020 or 1025 hot rolled, pickled and oiled steel, 3⁄16 in. thick. After forming, drilling and degreasing, the brackets had been given a coat of black primer.

To close the holes, arc welding was tried, but proved unsatisfactory. The weld metal and backing plate fused, and considerable cleanup was necessary after welding. Also, the primer had to be removed from around the holes, because it caused spatter during welding. Gas welding not only avoided these difficulties but also avoided subsequent grinding of weld surfaces. Operating conditions for gas welding are tabulated below Fig. 22.



Welding rod	⅛ in., RG45
Torch	Positive-pressure type
Tip-orifice diameter	0.0827 in.
Acetylene pressure	7.5 psi
Oxygen pressure	15 psi
Flame adjustment	Neutral, to slightly reducing
Welding position	Flat
Production rate	12 to 14 pieces per hour

Fig. 22. Bracket salvaged by gas welding incorrectly drilled holes (Example 519)

Altering equipment to make it suitable for new uses is another application for gas welding.

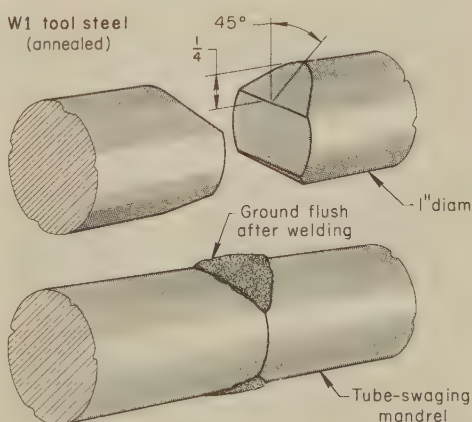
Example 520. Altering Tube-Swaging Mandrels (Fig. 23)

Tube-swaging mandrels were lengthened by welding extension pieces to them. The mandrels were made of annealed W1 water-hardening tool steel (0.85% C), and ranged in diameter from ½ to 2 in. Attempts to join the extensions to the mandrels by arc welding were unsuccessful. Partial-penetration gas welds, as shown for a 1-in.-diam mandrel in Fig. 23, provided adequate strength during swaging, and simplified separation when the extra length was no longer required. Gas welding was successful because it provided better control over the heating and cooling cycle.

Welding procedure was as follows:

1 Bevel both sides of each bar 45° (see Fig. 23), fit, and tack weld.
2 Preheat to 600 F for a distance of 4 in. on both sides of the joint. Use temperature-indicating crayons.
3 Weld both sides of joint, maintaining temperature, as above.
4 Immediately after welding, wrap joint in asbestos rope and allow to cool to room temperature.
5 Remove insulation and heat to 1050 F; hold at temperature for ½ hr. Use gas torch and temperature-indicating crayons.
6 Cool in air.

Operating conditions used for welding 1-in.-diam mandrels are given in Fig. 23.



Welding rod	3⁄32 in., RG60
Torch	Injector type
Tip-orifice diameter	0.0760 in.
Acetylene pressure	9 psi
Oxygen pressure	40 psi
Flame adjustment	Neutral

Fig. 23. Joint preparation and weld used for lengthening a tube-swaging mandrel (Example 520)

Preheating and Postheating

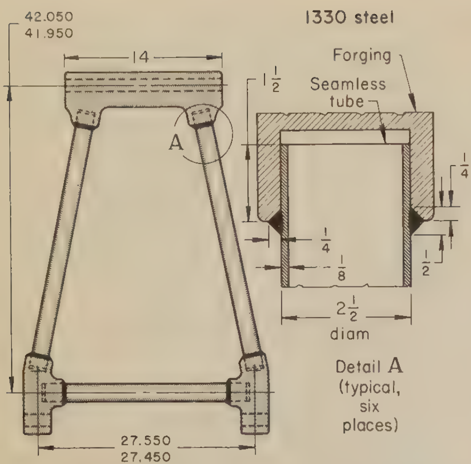
Preweld and postweld heat treatments are not usually required to reduce the hardness of low-carbon steel, but either or both treatments are beneficial and can be effective in avoiding or reducing distortion. Most steels that are gas welded fall within the low-carbon range.

Gas welding distributes a large amount of heat over a wide area. This results in relatively slow cooling rates and relatively low stress gradients, which, in turn, reduce the degree of hardening and the magnitude of residual stresses that are usually associated with welding heat cycles.

In Examples 518 and 520 in this article, preweld and postweld heat treatments were applied by using the heat of the gas flame. In the example that follows, gas welding eliminated cracking in a steel that had a carbon equivalent of 0.55 to 0.65% and could therefore be considered borderline as to the need for heat treatment.

Example 521. Use of Gas Welding To Eliminate Postweld Tempering (Fig. 24)

Aircraft landing-gear side-stay assemblies, shown schematically in Fig. 24, consisted of three end fittings of 1330 steel (0.28 to 0.33% C, 1.60 to 1.90% Mn) joined in the form of a trapezoid by three 1330 steel tubes measuring 2½ in. in outside diameter by ⅛ in. in wall thickness. The as-



Welding rod	3/32 in., RG60
Torch	Injector type
Tip-orifice diameter	0.0595 in.
Acetylene pressure	5 psi
Oxygen pressure	28 psi
Flame adjustment	Neutral

Fig. 24. Aircraft landing-gear support that was gas welded to eliminate need for postweld tempering (Example 521)

sembly was originally welded by the shielded metal-arc process; E7016 electrodes were used. Several assemblies cracked in a tube adjacent to a weld after a short time in service. Examination revealed that, in the heat-affected zone, hardness was as high as Rockwell C 50. The high hardness was caused by the chilling effect of the large mass of metal in the end fittings. A postweld tempering treatment at 1200 F to reduce the high hardness could not be used, because the tubes became distorted.

Local stress relief of the welded joints with a gas torch was then tried. This method was successful but laborious, and it was finally decided to gas weld the assembly. Hardness tests in the area of the welded joint showed that the maximum hardness in the heat-affected zone was 285 Brinell (Rockwell C 29). This was only moderately higher than the hardness of the end fittings and tubes, which had a hardness of 223 Brinell (Rockwell B 98). The improvement was believed to result from the wider area heated during gas welding, which produced a lower temperature gradient. Operating conditions for gas welding are given with Fig. 24.

Bridging Gaps in Poor Fit-Ups

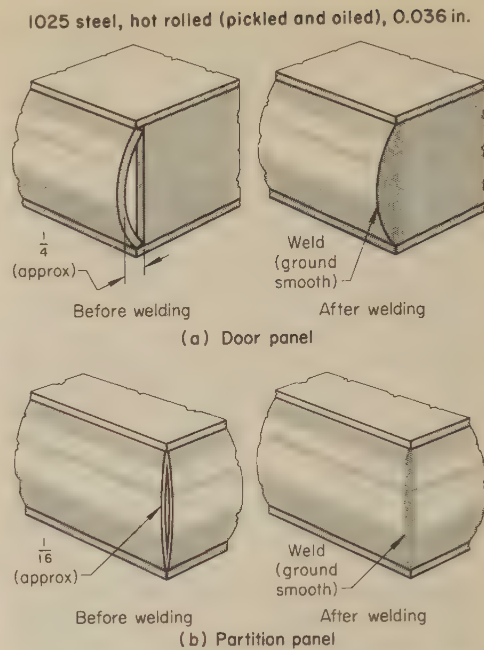
The ability to control the flow of molten weld metal in gas welding provides a high degree of versatility in bridging large gaps caused by a poor fit-up. By manipulation of the gas torch, weld-metal temperature can be held to the minimum, and the pressure of the gas flame can be used to help support the weld puddle in any position, including overhead.

The two examples that follow describe how gas welding was used to bridge gaps in fit-up. In the first example, gas welding was standard procedure; in the second, it was optional.

Example 522. Use of Gas Welding To Produce Neat Welds Where Fit-Up Was Poor (Fig. 25)

Partitions and partition doors, such as those used for office cubicles or lavatory stalls, were produced as panels consisting of two sheets of 1025 steel separated approximately 1 in. by formed strips that were fitted around the sides. Figure 25 shows a door panel and a partition panel before and after welding. The door panel, Fig. 25(a), had rounded strips down the sides and flat strips at the top and bottom. Where the rounded and flat strips intersected at the corners, a gap was formed in the shape of a circular segment with a ¼-in. rise. The partition panel, shown in Fig. 25(b), had rounded strips on all sides. These strips intersected in a mitered joint having a gap that was usually not more than 1/16 in. wide. The gaps in both types of panels were filled by gas welding as the strips were joined to the sheet. This method was easy to use and it produced smooth welds that required little grinding or finishing.

The gaps with the ¼-in. opening required 12 sec to weld. A small spacer was used to help fill the gap. The mitered joints required 9 sec to weld. Two men usually worked together on each panel. Other welding conditions were the same for both panels (see table with Fig. 25).



Welding Conditions
(For both panels, except where noted)

Welding rod	1/16 in., RG60
Tip-orifice diameter	0.0465 in.
Acetylene pressure	5 psi
Oxygen pressure	17 psi
Flame adjustment	Neutral, to slightly reducing
Number of passes	One
Welding time, door panel	12 sec
Welding time, partition panel	9 sec
Grinding time, door panel	15 sec

Fig. 25. Panels that were gas welded to obtain a neat joint despite gaps of varying size (Example 522)

Example 523. Gas Welding of Corner Joints in Tread Plate (Table 7)

Steps for the cab-door entrance of trucks were formed from single sheets of 16-gage (0.060 in.) four-way tread plate of hot rolled, low-carbon steel. The steps had flanges 1½ in. deep on all four sides. A closure weld was required at each of the four corners. Both arc welding and gas welding were used. When the corners were tightly formed, either process produced satisfactory joints, but because of the nonuniform cross section of the tread plate, accurate bending was difficult and large gaps often occurred at the corners. Under these conditions, gas welding was preferred. Gaps were filled and seams were welded in a single pass.

The welding conditions listed in Table 7 show gas pressures that are higher than those normally recommended for the tip-orifice diameter used. The pressures were reduced by adjustments of the inlet valves on the torch to give the desired flame characteristics. It was believed that higher welding speeds could be obtained by this means than by adjusting the gas regulators to the recommended gas pressures.

Example 508, page 573, describes another application where gas welding bridged gaps when fit-up was poor.

Table 7. Conditions for Gas Welding Corner Joints in Tread Plate (Example 523)

Base metal	Low-carbon steel
Thickness of base metal	0.060 in.
Welding rod	3/16 in., RG60
Torch	Equal pressure
Tip-orifice diameter	0.0675 in.
Acetylene pressure	12 psi
Oxygen pressure	45 psi(a)
Flame adjustment	Neutral
Welding position	Flat
Welding time per joint	30 sec

(a) High regulator setting was preferred by welder for fast production; however, flame was adjusted to neutral at the torch.

Safety

The gases employed in gas welding may form explosive mixtures if incorrectly handled, and burning of these gases must be controlled within recommended limits for safety of the welder and surrounding property.

The incorrect operation of gas welding equipment by untrained personnel can cause serious accidents. Therefore, before gas welding equipment is installed or operated, the safety rules regarding its use should be thoroughly learned.

Federal, state and local governments have adopted many safety rules that are legally enforceable. In addition, equipment manufacturers, gas suppliers, and regulatory agencies have cooperated in the publication of documents regarding safety in gas welding, with which the user should be familiar. The major sources of safety rules and recommendations are:

"Safe Handling of Compressed Gases", Compressed Gas Assoc., Inc., New York, Pamphlet P-1, Third Edition, 1956

"Oxygen-Fuel Gas Systems for Welding and Cutting", National Fire Protection Assn., Boston, Bulletin No. 51, 1964

"Safety in Welding and Cutting", American Welding Society, New York, ANSI Standard Z49.1–67, 1967. Also available from American National Standards Institute.

"Gas and Electric Cutting and Welding", American Petroleum Institute, New York, Accident Prevention Manual No. 3, Second Edition, 1953

"Storage and Handling of Liquefied Petroleum Gases", National Fire Protection Assoc., Boston, Bulletin No. 58, 1965

"Recommended Safe Practices in Cutting and Welding", Air Reduction Co., Inc., New York, Booklet No. ADE 872M, 1967

"The Oxy-Acetylene Handbook", Linde Co., Div of Union Carbide Corp., New York, 1960. [Pages 66 to 102 give precautions to be followed in using oxyacetylene equipment, and general precautions in gas welding and cutting.]

"Safe Practices — Gas Welding and Cutting Equipment", U. S. Dept. of Labor, Bureau of Labor Standards, Washington, D. C., Occupational Safety Chart No. 5

"Safe Practices for Installation and Operation of Oxyacetylene Welding and Cutting Equipment", Compressed Gas Assn., Inc., New York

A. N. Kugler, "Oxyacetylene Welding and Oxygen Cutting Instruction Course", Book 1 – Lectures; Book 2 – Exercises (published in one volume), Airco Welding Products Div., Air Reduction Co., Inc., New York, 1966.

Oxyacetylene Pressure Welding

OXYACETYLENE pressure welding is a process in which heat from oxyacetylene flames is used in conjunction with pressure to produce a solid-phase weld. Common applications include joining pipe sections, aircraft landing-gear components, railroad rails, and drill bits (to shanks). Most higher-melting alloys, including carbon and low-alloy steels, stainless steels, and heat-resisting alloys, can be successfully oxyacetylene pressure welded. The process has not proved successful for welding aluminum and magnesium alloys.

Principles of Operation. Although there is more than one method of oxyacetylene pressure welding, this article deals only with the closed-gap method.

Closed-gap welding is accomplished by either of two techniques. In one, called single-pressure welding, first the workpieces are butted together under a pre-established imposed pressure, and then the joint is surrounded with oxyacetylene torches to heat it until a given amount of upsetting has taken place. In the other technique, called double-pressure welding, the workpieces are butted together under an initial pressure, the joint is heated to a given temperature, and then the pressure is increased to accomplish the upsetting. Workpieces being heated for closed-gap oxyacetylene pressure welding are shown schematically in Fig. 1.

Advantages. Oxyacetylene pressure welding is faster than welding that entails fusion, and does not develop a cast structure in the weld zone. No inclusions or porosity are introduced during welding, and no molten metal is squeezed out as flash (as in flash welding). The metal in the weld zone is capable of the same response to heat treatment as the base metal. Susceptibility to cracking is minimized, because the temperature gradients developed during welding are not steep.

Limitations. Oxyacetylene pressure welding is slow compared with other pressure welding processes. Butting surfaces of the workpieces must be flat, parallel and clean, thereby increasing the cost of surface preparation.

Bars up to 3-in. diam and tubes as large as 25-in. OD have been welded by the closed-gap method. However, in welding thick-wall tubing or large-diameter bars, time is required for transmitting enough heat inward to metal farthest from the surface. This difficulty can be alleviated by the use of a tapered joint design.

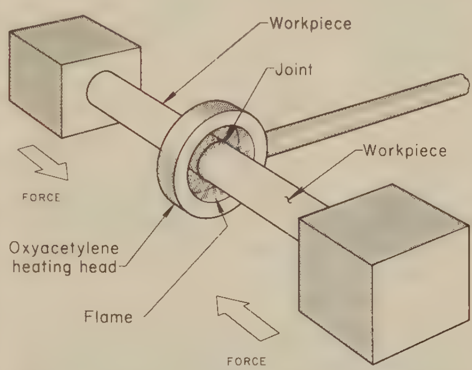


Fig. 1. Setup for heating workpieces for closed-gap oxyacetylene pressure welding

Table 1. Typical Conditions for Oxyacetylene Pressure Welding of Carbon Steel Pipes (a)

Wall thickness, in.	Welding time, sec	Total shortening, in.	Pipe-end bevel
0.187	45	0.25	4°
0.203	50	0.265	4°
0.238	55	0.300	4°
0.250	60	0.312	5°
0.375	90	0.412	6°

(a) Using the double-pressure method, with initial pressure 1000 psi of pipe cross section and final pressure 4000 psi of pipe cross section.

Joint Design. The butt ends of thicker sections (tube walls thicker than ¼ in. or solids thicker than ½ in.) are usually tapered. Tapering serves two purposes: (*a*) it facilitates heat penetration, and (*b*) it helps to control the shape of the upset. Carbon steels are generally beveled to a 6° to 10° included angle, with the open side, or gap, being exposed to the flames. This gap is closed during upset. For alloy steels, a much flatter included angle (140° to 150°) is used on outside diameters, and an included angle of 140° to 170° is used on inside diameters when tubing is being welded.

Typical Procedure. A typical sequence of operations for oxyacetylene pressure welding of hollow, 4135 steel landing-gear components by the closed-gap method is as follows:

1. The butting surfaces of parts are tapered on the outside and inside diameters to control upset contour, and are machined to a finish of 100 micro-in. or smoother.
2. Parts are loaded into the welding machine, and accuracy of alignment is checked by inserting a sheet of vellum between butting surfaces and pressing them together. When pressure is released, the vellum is examined for uniformity of contact around the entire circumference. Adjustments are made until uniformity is achieved.
3. The weld faces are cleaned with solvent and lint-free cloths, and a pressure of 4000 psi is applied to the weld area.
4. The heating head is brought into position and lighted, and the oscillating mechanism is started. The heating head is oscillated longitudinally (and sometimes radially, as well) to prevent localized overheating.
5. When the predetermined amount of upset has taken place, thrust and heat are discontinued and the part is allowed to cool to a black heat in the machine.

Typical conditions for oxyacetylene pressure welding pipes of various wall thicknesses are presented in Table 1.

Oxyacetylene Braze Welding of Steel and Cast Irons

OXYACETYLENE braze welding is a method of gas welding capable of joining many base metals but used primarily on steel and cast iron with a copper alloy filler metal (rod) and a flux. Braze welding is similar to torch brazing with a filler rod, except that joint openings are wider and distribution of filler metal takes place by deposition rather than by capillary flow. Equipment and some filler metals used in braze welding are the same as those used in torch brazing (see article that begins on page 619).

In braze welding of ferrous metals, the base metal is not melted. The filler-to-base-metal bond is the same as in torch brazing. Flux is applied to the joint surfaces, which, together with the surrounding area, are preheated to the point where the filler metal will wet or "tin" these surfaces. During welding, tinning precedes the weld puddle.

Applicability

Braze welding is used for making groove, fillet, plug or slot welds in metal ranging from thin sheet to heavy castings. Weld layers can be built up, as in gas welding.

The process is often used as a low-temperature substitute for gas welding or a low-cost substitute for brazing. Braze welding resembles brazing in two respects: (*a*) nonferrous filler metals are used, and (*b*) bonding is achieved without melting the base metal. On the other hand, braze welding resembles welding because it can be used for filling grooves and for building up fillets as may be required.

Major advantages of braze welding include: (*a*) joints are made at lower temperature than in gas or arc welding, thus minimizing thermal stress and distortion, as well as susceptibility to cracking; (*b*) the weld deposit is relatively soft and ductile, providing machinability and low residual stress; (*c*) joints with good strength and generous fillets can be produced (fillets often add strength for specific types of loading in service); and (*d*) the equipment is simple and well-suited to on-site repair applications.

Disadvantages of braze welding are: (*a*) weld and base-metal colors do not match; (*b*) weld strength, while usually adequate, is limited by the strength of the copper alloy used, and thus to service below 500 F; (*c*) joints are subject to galvanic corrosion and to differential chemical attack.

Braze welding is very often used in production joining applications; three are described in Examples 524, 525 and 526 in this article. The process is

Table 1. Compositions of Filler Metals Used for Braze Welding (AWS A5.7-69)

AWS classification	Composition, % (total other elements, 0.50% max) Cu(a)	Zn	Sn	Mn	Fe	Si	Ni(b)	P(c)	Al(c)	Pb(c)
RBCuZn-A	57-61	Rem	0.25-1.00	(d)	(d)	(d)	...	...	0.01	0.05
RCuZn-B	56-60	Rem	0.8-1.1	0.01-0.50	0.25-1.2	0.04-0.15	0.2-0.8	...	0.01	0.05
RCuZn-C	56-60	Rem	0.8-1.1	0.01-0.50	0.25-1.2	0.04-0.15		...	0.01	0.05
RBCuZn-D ...	46-50	Rem	...	...	...	0.04-0.15	9.0-11.0	0.25	0.01	0.05

(a) Including silver. (b) Including cobalt. (c) Maximum; included in the 0.50% max total of other elements. (d) Included in the 0.50% max total of other elements.

also used extensively for repairing broken or defective steel and cast iron parts (see Example 527). Braze welding is sometimes used for repairing cast iron castings in the foundry, although the color mismatch imposes a restriction on its use for this purpose.

Another frequent application of braze welding is in machine shops, for correcting machining errors or modifying in-process parts.

Shop maintenance departments and toolrooms use braze welding for repairing tools and pieces of equipment ranging from small hand tools to large cast iron press frames.

Mobile repair units such as those that accompany grain-harvesting crews usually carry equipment for braze welding so that harvesting machinery can be quickly repaired in the field when damaged.

Flame Adjustment

For carbon steels, the oxyacetylene flame for braze welding is adjusted to the neutral condition. For cast irons, the flame is adjusted to a slightly oxidizing condition by increasing oxygen or decreasing acetylene flow, which reduces the telltale acetylene "feather". When the feather disappears and the inner cone becomes slightly necked, the flame is oxidizing. This type of flame removes the graphite from surfaces of cast iron.

Air is not used as the combustion agent in braze welding, because it results in slow heating.

Filler Metals

The four copper-zinc or copper-zinc-nickel filler metals for which compositions are given in Table 1 are those most often used for braze welding. These four compositions are available as welding rods in the standard diameters from 1/16 to 1/4 in.; length is usually 36 in. The order in which the four filler metals are listed in Table 1 is roughly that of increasing tensile strength. All-weld-metal tensile strengths of the compositions shown range from approximately 50,000 to 70,000 psi. Melting temperatures of these alloys range from about 1600 to 1800 F.

RBCuZn-A (naval brass) rods contain up to 1% tin, which improves strength and corrosion resistance. These filler-metal rods are especially suited for use with oxyacetylene, and are considered as general-purpose rods for braze welding of steel and the various grades of graphitic cast iron.

RCuZn-B (low-fuming bronze) rods are similar to RBCuZn-A, but contain additions of iron, manganese, silicon and nickel, which serve to increase strength, and to reduce vaporization of the zinc (hence the name "low-

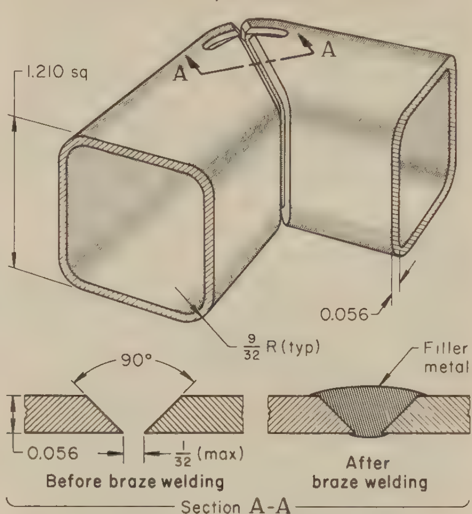


Fig. 1. Mitered corner joint in a tubular part used in manufacturing metal furniture. Poor appearance of plated joint was eliminated by a change in filler metal used in braze welding. (Example 524)

fuming"). RCuZn-B rods may be used for joining either steel or cast iron, and sometimes these rods are also used for surfacing steel or cast iron for wear resistance.

RCuZn-C rods are also low-fuming bronze rods, and are of the same composition as RCuZn-B except they do not contain nickel. RCuZn-C rods provide as-welded mechanical properties that are higher than those obtained with RBCuZn-A, and are widely used as general-purpose rods for braze welding of both steel and cast iron.

RBCuZn-D (nickel silver) rods have lower copper and higher nickel contents than those of the three other filler metals listed in Table 1. Because of this difference in composition, the deposit from an RBCuZn-D rod is whiter and is thus used for braze welding when closer color match is important. RBCuZn-D provides the highest as-welded strength of the four braze welding filler-metal alloys that are discussed here.

Joint Properties. Joints braze welded with one of the RCuZn filler metals have tensile strength at room temperature that usually ranges from 40,000 to 60,000 psi, depending on the filler metal used. The strength of the joint drops off very quickly at temperatures above 500 F. Color match with the base metal is not usually obtained, but where color is important the RBCuZn-D (nickel silver) rod is used. The bimetallic joint is subject to galvanic corrosion and is less resistant to alkaline solutions than the ferrous base metal.

The following example illustrates the use of braze welding in a conventional production operation on thin low-carbon steel, where difficulties were overcome by a change in filler metal.

Example 524. Change in Filler Metal That Improved the Appearance of Braze Welded Tubular Steel After Plating (Fig. 1)

Metal furniture parts made of low-carbon tubular steel conventionally were braze welded at corner joints. High rejection rates (25%) because of poor appearance were encountered when mitered joints of the type shown in Fig. 1 were nickel-chromium plated after braze welding. An investigation of the entire fabricating procedure showed that nearly all of the rejections could be eliminated by a change in filler metal. Details of the original procedure, the causes of rejections, and the revised procedure are discussed in the paragraphs that follow.

Preparation for braze welding was the same for both procedures. Tubing joints were sawed at a 45° angle, clipped at the corners for bending, and press formed at the outer side, as shown in Fig. 1. The joint edges were then beveled at 45° on all four sides. Without cleaning, the parts were assembled in a fixture to give a 1/32-in. maximum clearance at the joint. An oxyacetylene torch with an 0.0595-in.-diam tip was used with both procedures. In both cases, flux was added by gas fluxing through the flame. [Gas fluxing is described on page 629, in the article on Torch Brazing of Steel.]

In the original procedure, a rod of copper-zinc alloy RCuZn-C was used as filler metal, the joint being braze welded on all four sides. Before being plated, the weld was ground flush, buffed and chemically cleaned. Cleaning time varied because the manual braze welding operations were not uniform as to heating time, and the amount of smut left on the parts varied accordingly. The following difficulties occurred during cleaning and plating.

1. Conventional alkaline and acid solutions used in the cleaning process attacked the filler metal, causing voids and, in some assemblies, roughness, all of which were apparent after plating.
2. Time of exposure during cleaning was critical. Overexposure caused severe etching. Cleaning time was difficult to control because of lack of uniformity in heating during brazing.
3. Because of the softness of the filler metal, feather edges were left on the surface at the bond lines after grinding and buffing. The feathers were etched off during cleaning, but a sharp ridge was left that became an area of apparent nickel buildup during plating.
4. Color difference between filler and base metal was apparent after plating, outlining the joint.

By changing the filler metal to a rod of a different copper-zinc alloy, RBCuZn-D, the difficulties were overcome. Results of this change were:

1. The filler metal was less susceptible to attack during cleaning; voids and roughness were reduced to an acceptable level.
2. Cleaning time was less critical, giving the operator more latitude in removing smut.
3. The filler metal was harder and less likely to feather during grinding. The roughness resulting from buildup of nickel was greatly reduced.
4. Color match was improved, making the joint less noticeable.

The improvements reduced the rate of rejection after visual inspection to less than 1%. This saving more than offset the higher cost of the RBCuZn-D filler rod. In addition, higher joint strength was obtained. The change did not affect the production rate of 400 welds per 8-hr shift.

Fluxes

Fluxes for braze welding are not the same as those used for capillary brazing. Because the temperatures used in

braze welding (often higher than 1800 F) are higher than those used in most capillary brazing, and because the time of exposure to elevated temperature is longer in braze welding, the flux used must have a higher melting point and be able to withstand sustained exposure at the higher temperatures.

There are no standard specifications for braze welding fluxes. The few existing government specifications are based on composition, and the fluxes so specified are not considered as effective as the proprietary flux formulations that are available commercially. Three types of flux are in general use:

1. A basic type of flux, which simply facilitates braze welding by cleaning the base metals and aiding in the tinning operation
2. A flux, available in paste form, that performs the functions of the basic flux described above and, in addition, suppresses the formation of zinc oxide fumes from the filler metal
3. A flux, sometimes called a tinning flux, that is formulated expressly for use in braze welding of gray or ductile iron.

The first two of the above-listed fluxes are generally satisfactory for braze welding of steel and malleable iron. The second type is sometimes used with copper-zinc filler metals in capillary brazing. The third type contains iron oxide or manganese dioxide, either of which combines with the surface carbon of the gray and ductile irons; consequently, this type of flux is preferred for braze welding these cast irons.

Application of flux is done in any of four ways: (*a*) dipping the heated filler-metal rod in the flux, (*b*) brushing flux on the joint before brazing, (*c*) using flux-coated filler-metal rods, or (*d*) fluxing through the gas flame (see "Gas Fluxing" on page 629, in the article on Torch Brazing of Steel).

The use of flux-coated filler rods or gas fluxing eliminates the fluxing operation and ensures uniform application. Gas fluxing is used chiefly on steel in production (see Examples 524 and 526).

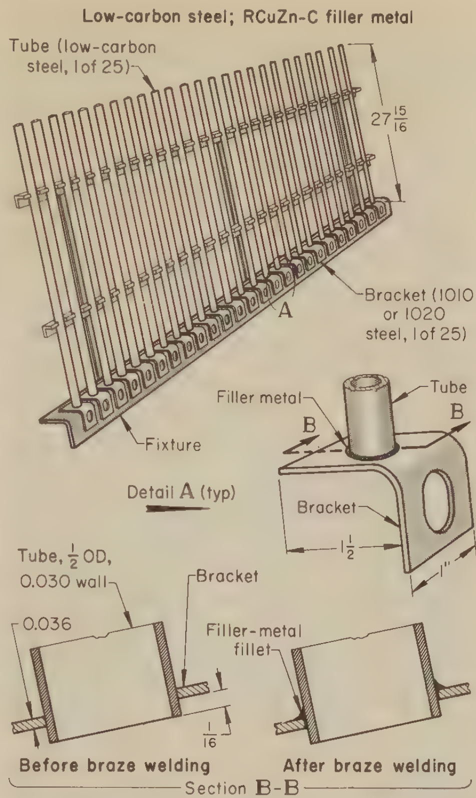
Joint Preparation

In base metals thicker than about $\frac{3}{32}$ in., the edges of butt joints for braze welding are prepared with a 90° or a 120° V-groove, to provide a wide bonding area. Fillet, plug and slot welds present naturally open faces. Edge preparation in base metals less than about $\frac{3}{32}$ in. thick can be optional; either a square groove with a root opening comparable to the thickness may be used, or a V-groove may be cut. The V-groove makes it possible for the braze welding operator to see whether the joint is properly filled; this is not always possible in torch brazing.

In applications involving thin joints with parallel-side joint surfaces and relatively close clearances, it is sometimes difficult to determine whether the joining process qualifies as brazing or braze welding, because there is some capillary action.

Cleaning Before Braze Welding

For satisfactory results in braze welding, joint edges must be as clean as possible before the operation begins. In order to obtain maximum bond strength, the joint surfaces must be bright and free of oil, rust or other foreign matter. Also, the metal surrounding the joint edges must be cleaned, both on bottom and on top.



In braze welding, production rate and joint quality were both improved in comparison with those obtained in the joining method previously used, shielded metal-arc tack welding.

Fig. 2. Tube-and-bracket assemblies that were oxyacetylene braze welded on a 25-assembly fixture, at the rate of five fixture loads per hour (Example 525)

The use of a salt bath is best for cleaning any of the cast irons prior to braze welding, just as it is for brazing (see the discussion of cleaning procedures on page 661 in the article on Brazing of Cast Irons). If a salt bath is not available, however, the procedures described in the following paragraph are reasonably satisfactory.

If the surface of cast iron has been ground, the graphitic smear can be removed by quickly heating the surface until it is dull red in color and, after cooling, going over the surface with a wire brush. If greasy or oily cast iron is ground, some of the grease or oil may penetrate the surface. If this occurs, the resulting film should be removed by painting the surface with chemically pure hydrochloric acid. After 15 minutes, the surface must be scrubbed with a wire brush and cold clean water.

Preheating and Postheating

Although it is not always necessary, iron castings may be preheated before being braze welded, to ensure success of the operation. The preheating may be local or general, depending on the size of the casting. Large castings require extensive preheating. A black preheat, or a low red heat visible in darkness (obtained at approximately 900 F), is generally used. It has been advantageous in some applications to preheat to as high as 1650 F, but temperatures above 1000 F may have an adverse effect on the wetting action of the filler metal, because of oxidation of the surfaces before braze welding.

No postheating is necessary after braze welding of cast iron. However, cooling of the braze welded assemblies is preferably retarded by wrapping them with asbestos or by the use of similarly effective methods.

Braze Welding of Steel

Braze welding of steel is faster than gas welding, because braze welding requires less heat. Overheating of the base metal must be avoided, to prevent the filler metal from failing to wet the joint surfaces. Low-carbon steels are heated no higher than 1350 F before the filler metal is deposited. Although the filler-metal alloys used in braze welding melt at temperatures between 1600 and 1800 F, the only rise in the temperature of the base metal is that incidental to deposition.

The low peak temperatures in braze welding reduce the probability of distortion and avoid the problem of melt-through in thin metals. The next example describes an application in which braze welding eliminated melt-through, increased production rate, and improved product appearance and quality for a steel tube-and-bracket assembly.

Example 525. Use of Braze Welding To Replace Arc Tack Welding (Fig. 2)

Joining 20-gage (0.036-in.) brackets of low-carbon steel to $27\frac{15}{16}$-in. lengths of ½-in.-OD by 0.030-in.-wall tubing of the same material was originally done by shielded metal-arc tack welding. Figure 2 shows a typical tube-and-bracket assembly.

The tack welding operation was generally unsatisfactory. When a single-part fixture was used, the operation was too slow. By using a multiple-part fixture, production was speeded up, but inaccurate arc strikes and melt-through resulted in many rejects and some service failures. The welder found it awkward and time-consuming to raise and lower his welding hood for each tack weld, but failure to do so caused erratic arc control.

By changing to braze welding, it was possible to use a 25-part fixture (Fig. 2) and to braze weld each part successively without interruption. A lightly flux-coated, low-fuming bronze rod (RCuZn-C) was used to deposit a fillet weld that gave a much better appearance than the tack welds and was stronger. The oxyacetylene torch was adjusted for maximum heating with a neutral flame. In playing the flame on the joints, the torch tip was generally pointed in the direction of welding progress, making a separate preheating operation unnecessary.

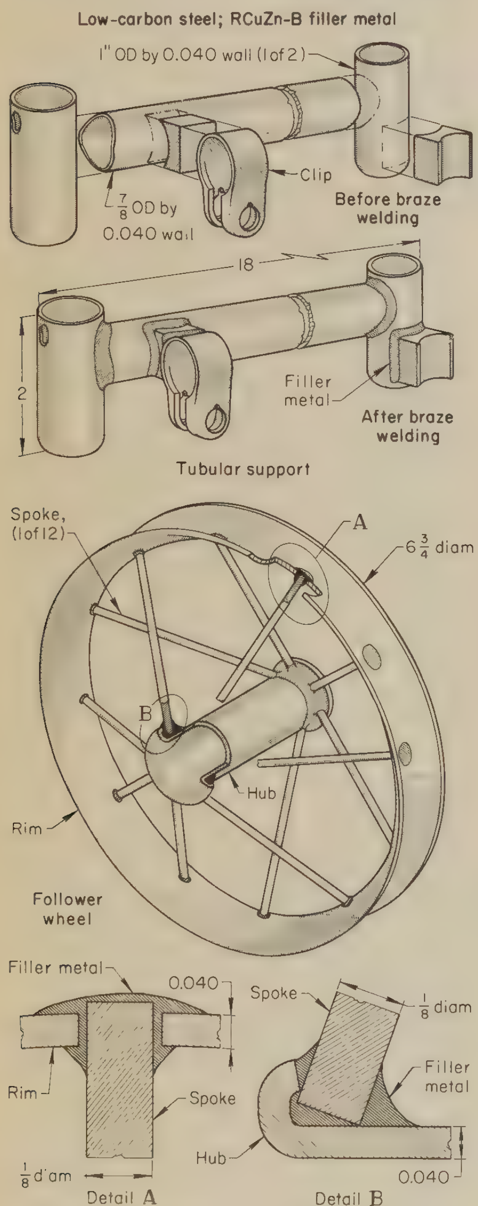
In addition to achieving a satisfactorily high production rate (125 pieces per hour, including loading and unloading), rejections were negligible. After several years in service, no tube failures were reported.

Production braze welding of metal furniture and similar products that are to be plated requires joints that are free of surface oxidation, overheated flux, and smut film. In addition to pickling, it may be necessary to grind, brush, buff and polish the joint for satisfactory plating. The cost and delay of the latter operations often can be avoided by using the procedures described in the next example.

Example 526. Copper-Zinc Braze Welding With Gas Fluxing (Fig. 3)

Braze welding with gas fluxing was the most practical method of joining the various low-carbon steel parts used in the manufacture of chromium-plated invalid wheelchairs. More than 200 joints per chair were involved in this assembly of tubing, wire, formed sheet, and formed or machined bar stock. Two typical structural subassemblies are shown in Fig. 3. The tubular support required five welds: tube-to-tube (2), tube-to-fitting (2) and fitting-to-fitting (1). The follower wheel required 12 spoke-to-rim and 12 spoke-to-hub welds. The major requirements for both subassemblies were strength, smooth appearance, platability, and speed of production.

Strength requirements were not difficult to meet, because the joints were designed so that a smoothly filleted weld deposit would provide more than adequate strength. Meeting the other requirements was a matter of skill in consistently applying optimum technique.



Torch type	Oxyacetylene
Tip-orifice size	No. 57 drill (0.043-in. diam)
Filler metal	⅛-in.-diam wire, RCuZn-B
Flux	Gas flux
Preheat and postheat	None
Assembly and brazing time	3 minutes
Production, tubular supports	120 per 8-hr shift

Fig. 3. Manually braze welded subassemblies used in the manufacture of wheelchairs. Smooth fillets and absence of overheated metal were essential. (Example 526)

Joining the parts of the tubular support shown in Fig. 3 was done at one of seven stations, each of which was supplied with oxygen and acetylene from two pipelines leading from cylinders equipped with manifolds. At each station, the tooling and fixturing used for assembling and aligning the workpieces was mounted on a pedestal adjusted to a height convenient for the operator in the standing position.

The efficiency of the procedure was based on eliminating operations that would slow production, add cost or produce questionable results. Thus, to avoid the separate application of a flux and subsequent manual flux cleaning, gas fluxing was used (see Fig. 10 and accompanying text on page 629 in the article on Torch Brazing). In addition, gas fluxing made it possible to eliminate postweld grinding, sanding and buffing prior to electroplating.

The low-carbon steel parts were processed through a solvent cleaning tank, dried, and stored at respective braze welding stations. Parts were assembled manually in a fixture and held in alignment by toggle clamps. Joint clearances for the tubular part varied from about 0.005 to 0.015 in. before heating, except for the joint at the circular clip (Fig. 3), which flared out to about ⅛ in. The oxyacetylene torch flame was adjusted to neutral with a very slight acetylene feather. Because of the brilliant green flame resulting from the presence of the flux in the fuel gas, suitably tinted goggles were worn during the adjustment.

The flame was "brushed" around each joint for a few seconds, heating the area and depositing a thin film of flux. A rod of copper-zinc filler metal, RCuZn-B, was touched to the joint at several places, heated and melted. The molten filler metal flowed through the remaining joint area and formed well-rounded fillets. Care was exercised to avoid overheating either the base metal or the filler metal. Overheated areas on the assembly, which were readily identified by burned and blackened flux and metal, could not be plated without considerable dressing. Since skilled operators could avoid overheating, the few overheated assemblies encountered were not worth the cost of reclaiming, and were scrapped.

After braze welding, the assemblies were sent through a sequence of washing, pickling and nickel-chromium plating. Hot-water washing was all that was necessary to remove the flux. The principal processing conditions for the tubular part are summarized in the table accompanying Fig. 3.

Repair of Iron Castings

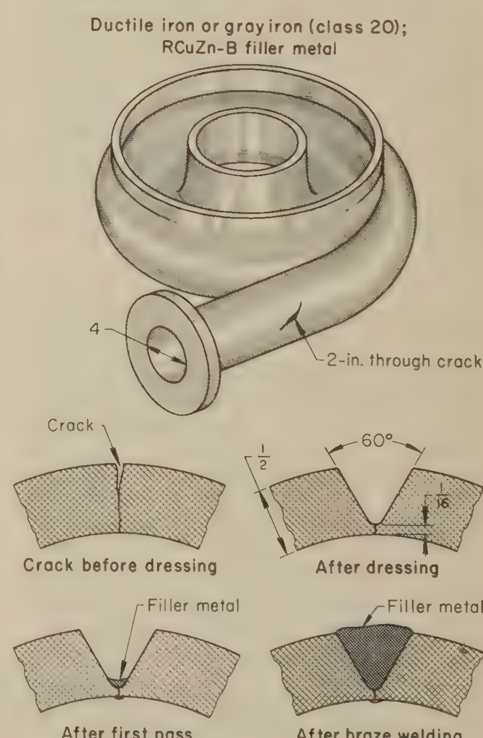
Unlike other welding processes, braze welding with copper alloy filler metals is equally effective on any type of cast iron. Peak temperatures of the base metal in braze welding can be low enough to avoid, or at least to cause very little, transformation during the heating cycle. Brittle transformation products in the heat-affected zone of the joint, therefore, can be largely prevented. The weld-metal strength is in the strength range of the gray irons, the ferritic malleable irons and the lower-strength ferritic ductile irons. Tension tests of braze welded joints have sometimes shown a disturbingly frequent occurrence of parting at the bond line, but this is generally attributed to improper cleaning, fluxing or tinning, and it emphasizes the need for care and skill.

The low temperature requirements of braze welding make the process particularly suitable for joining malleable iron. Cast iron base metal rarely needs to be preheated to more than 1000 F, and lower temperatures are often used. In fact, the base metal itself determines the correct preheating temperature; if too hot or too cold, the filler metal will not wet (or "tin") the joint. The heat added during braze welding is normally of short duration.

The principal drawbacks of braze welding as applied to cast iron are: (*a*) the color of the copper alloy filler metal does not match that of the iron; (*b*) the corrosion resistance of the weld metal differs from that of the base metal, being particularly low when the weld metal is exposed to strong alkalis; (*c*) galvanic corrosion, due to dissimilar metals, may be a problem; and (*d*) the strength of a braze weld falls off rapidly with increasing temperature, so that the service temperature of the casting is limited to 500 F max.

Braze welding is used to join cast iron to itself or to other metals for production assemblies, but it is more widely used for repairing castings worn or broken in service. In addition to its low cost, in comparison with the cost of gas welding with cast iron rods, the chief advantages of braze welding can be summarized as follows:

1 Low thermal stresses minimize the possibility of cracking in the cast iron, which is a brittle material.
2 Low peak temperatures avoid the formation of brittle transformation products encountered with other joining processes.
3 The copper alloy weld metal is sufficiently ductile to absorb most shrinkage stresses without cracking or parting at the bond.



Filler metal	⅛ in., RCuZn-B
Tip-orifice size	No. 36 drill (0.1065-in. diam)
Flame	Neutral
Preheat	1400 F, local
Postheat	None (slow cooling under insulation)

Fig. 4. Oil-soaked pump casting in which a crack was repaired by braze welding (Example 527)

4 Where preheating requirements can be met by local torch preheating, the repair can often be made in position.
5 Postheating requirements usually involve only slow cooling from the braze welding temperature.
6 Braze welding is better suited to the repair of malleable iron castings than is arc or gas welding.

The braze welding of cast iron usually requires extra care in joint preparation and cleaning. The two main considerations are the presence of graphitic carbon and the possibility of oil or other impregnation existing as a result of service. The best method of removing cracks or preparing broken edges is by chipping and abrasive blasting. Other methods of metal removal result in smearing of the graphite, which prevents bonding.

A salt bath offers the best method for cleaning cast iron (see the preceding section on Cleaning Before Braze Welding). However, smeared graphite as well as impregnations can be removed by heating the surface of the casting to a dull red heat (approximately 1200 to 1400 F). Heating the casting surface to this temperature range may cause the formation of surface oxides that prevent wetting by the filler metal; for this reason, the use of a tinning flux is helpful if heating has been used to remove graphite before braze welding.

The following example indicates the methods that were necessary for successful repair braze welding of an iron pump casting.

Example 527. Selection of Method for Repairing Oil-Soaked Pressure Castings (Fig. 4)

Centrifugal pump castings of either ductile or gray iron (see Fig. 4) were designed to pump transformer oil at 50-psi pressure. Defects, which sometimes became evident after the pump had been in operation, were difficult to repair because oil had penetrated deep into the material. The manufacturer found that, even after cutting out the defect, burning out the oil at high temperature and wire brushing the surface, neither gas welding nor arc welding produced a leaktight repair. Braze welding, however, proved successful. It was believed that some residue remained below the surface of the base metal after heating, and that in gas or arc welding, this residue caused excessive porosity during fusion of the base metal. Because the base metal was not melted in braze welding, a leaktight bond was made on the cleaned surface.

Figure 4 shows the location of a fine crack that was repaired by braze welding using the following procedure:

1 With an abrasive cutoff wheel mounted on a hand grinder, the crack was dressed out to form a 60° V-groove with a small radius at the bottom, leaving approximately 1/16-in. thickness, as in Fig. 4.
2 The inside of the pipe along the crack area was cleaned off using a rotary file.
3 The joint area was heated by an oxyacetylene torch to cherry red (approximately 1400 F), to burn off the oil.
4 The weld groove was wire brushed to remove all surface residue.
5 An oxyacetylene torch was then used to preheat the joint area to a cherry red (approximately 1400 F).
6 A 1/8-in. manganese bronze filler rod (RCuZn-B) was heated for a length of about 1 in. and dipped into a flux.
7 Heat was concentrated on the bottom of the groove until the filler metal started to wet the iron. A thin layer of filler metal was applied, penetrating to the inside of the pipe through the base metal at the bottom of the groove.
8 The remainder of the groove was filled, with the filler-metal rod being dipped into the flux as required.
9 After the joint was completed, the torch was slowly worked away from the joint so that the redness of the base metal disappeared slowly.
10 The joint area was wrapped in asbestos and allowed to cool slowly.

Other details are summarized in the table that accompanies Fig. 4.

Oxyacetylene Welding of Cast Irons

*By the ASM Committee on Welding of Cast Irons**

OXYACETYLENE welding is widely used on gray iron, to a smaller extent on ductile iron, and only to a minor extent on malleable iron. Cast iron filler metal is melted together with the base metal to form the joint.

An oxyacetylene flame has a maximum temperature of about 6000 F, which is several thousand degrees less than that of a welding arc. Gas welding is therefore slower, and results in greater heat input and wider heat-affected zones than those produced by arc welding. For this reason, high preheats of 1100 to 1200 F are generally used for gas welding of cast irons. However, for local repairs and small unrestrained castings, lower preheat temperatures (often as low as 800 F) may be used. Depending on the mass, composition and structure of the casting, postheating requirements vary from slow cooling to complete stress relief (1150 F) to full annealing (1650 F). Because of higher preheat, and thus lower cooling rates, gas welding produces less hardening in the heat-affected zone than does arc welding. Cast irons that are preheated, welded and slow cooled are readily machinable (important in much repair work).

Like the castings themselves, welds in gray iron castings have nil ductility. In a series of tests, joints in class 30 gray iron that were gas welded with RCI rods had a somewhat lower average tensile strength than the same joints gas welded with RCI-A rods or shielded metal-arc welded with ENiFe-CI electrodes. In these tests, the castings were preheated to 400 to 500 F for arc welding, and to 1100 to 1200 F for gas welding, and all welds were cooled slowly under insulation. In spite of the greater heat input and the high preheat temperatures used, welders skilled in gas welding of cast iron produced results comparable to the best arc welded joints.

In the same tests, joints in malleable iron that were gas welded using the ductile iron rod RCI-B were not of good quality. The poor results were attributed to: (*a*) the low melting point of the RCI-B rod (200 to 300 F lower than that of the base metal), and (*b*) hardening of the weld deposit, together with the reversion to white iron that takes place in the heat-affected zone.

Gas welding is not recommended for joining of malleable iron (see the section on Welding of Malleable and White Irons, on page 586).

Good results have been obtained in gas welding ferritic ductile iron with ductile iron rods. In production welding, however, the speed of gas welding cannot compare with that of arc welding. In addition, welds deposited by gas welding with cast iron rods usually are less machinable than nickel or nickel-iron welds deposited by arc welding.

Porosity, which is a common problem in gas welding, can be minimized by using a slightly reducing flame.

As a general practice, oxyacetylene welding has been used on cast irons for the following purposes:

1 Repair of minor casting defects in gray iron (see Example 528) and ductile iron. Minor surface blemishes in malleable irons are sometimes repaired; generally, however, oxyacetylene welding of malleable iron is avoided whenever possible.
2 Repair of service-incurred wear and damage (Example 529), mostly on gray and ductile irons.
3 Production of gray and ductile iron weldments involving either two parts made of cast iron, or one of cast iron and one of another metal (usually steel).

Repair of Casting Defects. The most common application of welding to cast iron is the repair of rough gray iron castings. Although the majority of this repair work is done by oxyacetylene welding, some is done by arc welding (see page 235 in the article on Arc Welding of Cast Irons). If repair welding is confined to correction of small defects that affect only the appearance of the casting, inferior mechanical properties and machinability of the weld are of no consequence. The defect must be in an unstressed area that requires no machining and, as a rule, should not extend through the section. Typical defects include sand holes, porosity, washouts, cold shuts, and shift.

Castings that have defects resulting from machining errors also can be repaired by oxyacetylene welding, provided that the heat of welding does not cause distortion. Usually, arc welding is preferred to oxyacetylene welding for correction of machining errors, because arc welding is faster, has a lower heat input (and therefore causes less distortion), and produces welds with adequate properties. Good color match of weld and base metal generally is an additional requirement.

Reclaiming defective castings by repair welding is common practice. One

*For committee list, see page 235.

Table 1. Chemical Compositions of Cast Iron Filler Metals Used for Oxyacetylene Welding of Cast Iron (AWS A5.15-69)

Classification	C	Si	Mn	Ni	Mo	P	S	Ce
RCI	3.25-3.50	2.75-3.00	0.60-0.75	Trace	Trace	0.50-0.75	0.10 max	...
RCI-A	3.25-3.50	2.00-2.50	0.50-0.70	1.20-1.60	0.25-0.45	0.20-0.40	0.10 max	...
RCI-B	3.25-4.00	3.25-3.75	0.10-0.40	0.50 max	...	0.05 max	0.03 max	0.20 max

foundry has reported that the average cost of repairing leaks in pressure castings was 9% of the selling price of the castings. The repairs were made by oxyacetylene welding, using a cast iron welding rod, to salvage castings that would otherwise have been scrapped. The 9% repair cost was allocated as follows:

Material 2.5%
Labor 1.5
Burden, including gas, electricity and amortization 5.0

Repair of Damaged Castings. Iron castings that have become cracked, broken or worn in service are regularly repaired by oxyacetylene welding. Braze welding (see the article on Oxyacetylene Braze Welding of Steel and Cast Irons, which begins on page 579) is used in many applications because of its simplicity and low preheat requirements and because color match is seldom important in such repair.

If welding must be done under adverse conditions, extra care and attention to procedural detail are required. Because repair of damaged castings often is a major welding operation, in that a considerable mass of base metal is subjected to high temperatures, preheating is required. A temporary oven around the part or a means of providing localized heating may be needed, depending on size and shape of the part, the required temperature, and duration of heating. (See Example 529, which describes an application in which gas welding was used in preference to braze welding for repairing a cracked press frame.)

Repair of Worn Castings by Hard Facing. Oxyacetylene welding is often used to repair (build up by hard facing) specific areas of worn gray or ductile iron castings. Malleable iron castings are not well suited to repair by hard facing.

Arc and braze welding are also used for this application; the choice among the three processes depends largely on service requirements and the equipment available. If the properties obtained are acceptable, braze welding is the logical choice, because the casting is far less likely to crack than when arc or oxyacetylene welded. The choice between arc and oxyacetylene welding for repairing worn castings by hard facing usually depends on the equipment available. Similar results can be obtained with both processes (see the section on Hard Facing on page 244, in the article on Arc Welding of Cast Irons).

The cost of repairing worn castings must be weighed against the cost of replacing them. Consideration must be given to the cost of building up cast iron, a relatively cheap material, with costly hard facing alloys.

In practice, however, there are cost considerations other than just the price of the casting; delays in getting replacement castings, and downtime for replacing a casting in a machine, are often more important. Repair by hard facing eliminates procurement delays, and saves downtime by prolonging casting life. A casting that has been hard faced by welding often lasts two to five times as long as the original casting.

Mill-roll journals, rolling-mill guides, wire-spinning rolls, and cast components of mills that process abrasive materials like cement and clay products are typical applications of repair by hard facing.

The overlay (hard facing) material applied to castings by oxyacetylene welding usually contains at least 3.0%, and more often 4.0 to 5.0%, carbon — which usually equals or exceeds the carbon content of the base metal. In addition to having high carbon contents, most hard facing materials also have high alloy contents. Most hard facing materials are proprietary alloys; three typical ones have nominal (iron-base) compositions, as follows:

3.9 C, 32.0 Cr, 6.0 Mo
4.1 C, 16.0 Cr, 2.0 Ni, 8.0 Mo, 1.0 V
4.3 C, 16.0 Cr, 6.0 Ni, 8.0 Mo

For other compositions of hard facing alloys, see Table 2 on page 154 in the article on Hard Facing by Arc Welding. Hard facing alloys such as the three listed above are available in rod form for welding with oxyacetylene.

Preheating the casting prior to welding the overlay is mandatory to prevent cracking. For castings having reasonably uniform sections, preheating to 650 to 700 F is sufficient; but for castings having a wide variation in section thickness, preheating in the range of 1100 to 1200 F is generally recommended. Time at preheating temperature should be sufficient to ensure that the casting has been uniformly heated.

Postheating is not necessary, but the welded casting must be cooled slowly. In preferred practice, the welded casting is immediately placed in a furnace maintained at or near the preheating temperature used, and then is cooled in the furnace. If a furnace is not available, the welded casting should be buried immediately in an insulating material such as lime or spent carburizing compound, and be allowed to remain buried until it has cooled to near room temperature.

Production of Assemblies. Design limitations and production problems sometimes can be overcome by welding iron castings to other iron castings or to steel. Some form of arc welding is usually preferred because it is fast, but oxyacetylene welding is also used.

Preparation of Castings

If a casting to be repaired has been in service, preparation of the casting for welding requires, in addition to edge preparation, the removal of surface contaminants. Oil, grease and paint should be removed with solvents, commercial cleaners or paint removers as required. Impregnated oil or other volatile matter can be eliminated by heating the casting or weld groove to approximately 900 F (dull red heat) for about 15 min and then wire brushing, grinding or rotary filing to remove the residue. Casting skin on surfaces adjacent to the joint area should be removed by grinding, chipping, shot blasting or rotary filing. Defects such as porosity, inclusions and cold shuts should be gouged out and the bottom of the cavity should be well rounded rather than V-shape.

Completely broken sections should be dressed to form a single-V joint, with a 1/16-to-1/8-in. root face to align the parts. Gas welding requires a V-groove with an included angle of 60 to 90°, to permit proper manipulation of the torch and welding rod. For heavy sections, a double-V joint should be prepared whenever feasible, with a root face at or near the center.

Preheating

By decreasing the rates of heating and cooling of the weld metal and adjacent base metal, preheating minimizes the formation of brittle microstructures in the zone around the weld, and thus reduces stresses that might cause cracking immediately after welding and in service. Softer, less brittle microstructures are obtained with high rather than low preheat temperatures. Recommended preheats are discussed in the individual sections of this article devoted to gray and ductile irons.

To ensure that the preheat temperature is maintained throughout the welding operation, it may be necessary to insulate the heated casting. Heat input from welding must not be permitted to increase the interpass temperature above the maximum preheat temperature, or welding must be stopped until the temperature drops to the preheat range. Temperature should be measured by contact pyrometers or temperature-indicating crayons at or near the weld zone and at one or more other places as required. (See also page 236 in the article on Arc Welding of Cast Irons, in this volume, for additional information on preheating.)

Postweld Heat Treatment

Postweld heat treatment may be either stress relieving or full annealing. Stress relieving at 1150 F and then furnace cooling to 700 F or lower is recommended whenever feasible. Full annealing at 1650 F produces greater softening of the weld zone and more nearly complete stress relief, but it also lowers the tensile strength of all but the softest irons.

Welding Rods

Cast iron rods used in the welding of cast iron should contain enough carbon and silicon to allow for losses of these elements during welding. The silicon content of the filler metal must be high enough to permit carbon to precipitate as free carbon during solidification and to promote a soft, machinable matrix as the weld cools to room temperature. Chemical compositions of

cast iron filler metals used for oxyacetylene welding of cast iron are given in Table 1.

Rods made of cast iron usually are 24 in. long and ¼ in. square, although rods ⅛ to ½ in. square are available.

The RCI filler metal and a number of proprietary rod compositions are used for welding gray irons of classes 20 to 35 (20,000 to 35,000 psi tensile strength). Gray irons that have tensile strengths of 35,000 to 40,000 psi can be welded with RCI-A filler metal, which is similar to RCI but also contains 1.20 to 1.60% nickel and 0.25 to 0.45% molybdenum. Many proprietary rods contain chromium, nickel, molybdenum, copper, or vanadium, either singly or in combination, to produce high-strength welds; carefully controlled procedure is required with these rods to avoid obtaining a hard weld deposit.

Two basic types of welding rods have been successfully used for welding ductile iron: RCI-B, which is generally higher in carbon and silicon content and lower in manganese than the gray iron rods and contains cerium as a nodularizing agent, and proprietary rods in which magnesium is used as the nodularizing agent.

Fluxes

A flux is required in gas welding of cast iron to increase the fluidity of the fusible iron-silicate slag, as well as to aid in the removal of the slag. Fluxes for gray iron rods are usually composed of borates or boric acid, soda ash, and small amounts of other compounds such as sodium chloride, ammonium sulfate and iron oxide. A mixture of equal parts of boric acid and soda ash, 2% ammonium sulfate and 15% powdered iron makes a satisfactory flux.

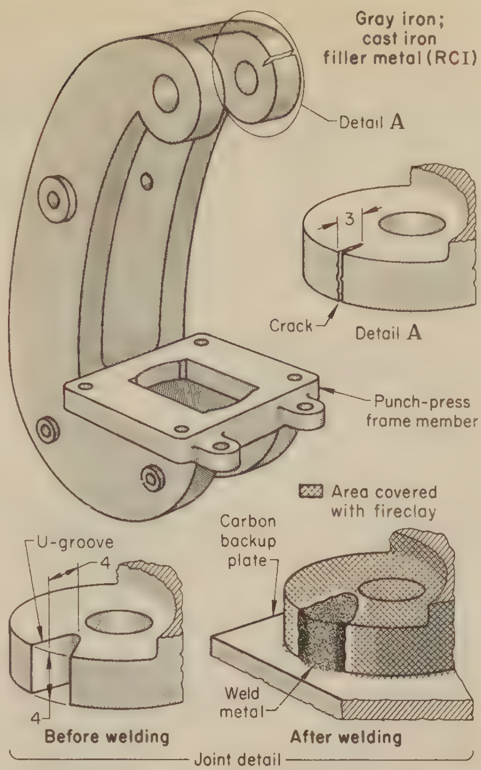
Fluxes suitable for welding ductile iron with a ductile iron rod are similar to those used for welding gray iron, but are formulated to produce a slag with a lower melting point. Some proprietary fluxes contain inoculants.

Welding of Gray Iron

Gas welding of gray iron generally is done for repair, but also can be done for production of simple assemblies. The cavity is first prepared for welding by the usual methods (see the section on Preparation of Castings) and then ordinarily is tested by liquid-penetrant or magnetic-particle inspection to ensure freedom from defects.

The casting preferably is preheated to 1150 F in a furnace and then covered with asbestos cloth, exposing only the cavity to be welded. If a furnace is not available, the casting can be covered with asbestos cloth and locally heated by gas flame.

A high-velocity torch that will produce a concentrated flame pattern, similar to that used for welding mild steel, should be used. The cavity surface is dusted with a thin layer of flux, the heated rod is dipped in flux and positioned in the cavity, and both are heated with an oxyacetylene torch adjusted for a neutral or slightly reducing flame. The rod and a small area of the cavity soften under the flame, and as



Filler metal	¼-in.-square rod, RCI
Flux	Proprietary(a)
Oxygen pressure	90 psi
Acetylene pressure	17 psi
Tip size	No. 16 drill (0.177-in. diam)
Preheat	1200 F
Postheat	1200 F for 6 hr
Welding time (total)	16 hr

(a) Mainly sodium borates and carbonates

Fig. 1. Repair of a large crack in a gray iron punch-press frame by gas welding under conditions given in table (Example 529)

the rod melts off and combines with the base metal, the torch and rod are slowly moved along the cavity. The flame should be directed at the bottom of the cavity with the tip held ¼ to ⅛ in. from the metal until a molten puddle up to 1 in. long begins to form. The torch is moved from side to side until the walls of the cavity start to melt into the puddle. This process is continued until the entire cavity is filled with weld metal ¹⁄₁₆ to ⅛ in. thick. It is advisable to play the welding flame back over the previously deposited metal to retard its cooling rate, to reduce residual stress, and to permit escape of entrapped gas.

Postweld stress-relieving is recommended, particularly for complex castings or where accurate machining will follow. The casting should be placed in a furnace that is at the same temperature as the casting, immediately upon completion of welding, and gradually heated to 1100 to 1200 F for one hour per inch of thickness; it may then be cooled to 500 F or below at a rate no faster than 50 F per hour. When the welded casting is not stress relieved, it should be cooled slowly either in a furnace or by covering it with asbestos paper, sand, or some other insulating material.

When class 30 irons are preheated to 1100 to 1150 F before gas welding, some fine pearlite and ferrite are present in the final weld metal and in the heat-affected zone; weld tensile strength approaching 30,000 psi and hardness less than 200 Bhn can be obtained. When class 40 irons are gas welded under similar preheat conditions, higher proportions of fine pearlite, less ferrite, and some cementite are present, and weld strength may reach 35,000 psi, with hardness as high as 200 Bhn. Although higher-strength irons containing chromium and molybdenum have been welded, welding rods compatible with these irons are not readily available. When specially made welding rods were used experimentally, weld-metal tensile strength up to 45,000 psi was obtained, but carbide formation, which caused cracking, was difficult to control. Welding generally is not attempted in gray iron stronger than class 50, because of the high probability of cracking.

Difficulty in machining is seldom encountered if high preheat and interpass temperatures are used. Class 40 irons usually can be gas welded to a hardness of 200 Bhn or less in weld metal and heat-affected zone. Cast iron welding rods provide good color match.

More welding of cast iron is done in foundry repair of defects in new castings than in any other type of application. Processes most frequently used are gas welding and shielded metal-arc welding. The example that follows describes a production-line repair setup that is typical of automotive foundries.

Example 528. Repair of Defects in Automotive Engine Blocks

In an automotive-engine foundry, defects in gray iron engine-block castings were repaired by gas welding at a rate of 16.9 castings per hour. The castings weighed about 225 lb each, measured 22 by 18 by 10 in., and had section thicknesses varying from approximately ³⁄₁₆ to ⅝ in. The welding was done to seal leaks and to repair surface imperfections that had been caused by sand inclusions. Repairable castings were moved by conveyor through six operations.

After shakeout, in order that defective areas would be visible after preheat, castings were inspected and marked for repair before being conveyed to a gas-fired tunnel furnace, where they were heated slowly to 1200 F and soaked for a minimum of 30 min. A cutting torch was then used for thoroughly cleaning out and preparing defective areas for welding.

Next, the cavities were filled in by oxyacetylene welding, using a ¼-in. cast iron rod for filler metal. Both cleaning and welding had to be done rapidly, since no welding was permitted if the casting temperature dropped below 850 F. Similarly, no welding was done if the temperature of the preheat furnace fell below 1150 F, or that of the postheat furnace fell below 1000 F. After welding, castings were conveyed to a furnace, where they were heated to 1050 F, and then were furnace cooled to 600 F over a period of at least 45 min. The final operation consisted of removing the flux deposit and grinding the weld surface flush.

For the repair of a cracked punch-press frame as described in the following example, gas welding was selected over braze welding for reasons of strength and appearance.

Example 529. Repair of a Cracked Punch-Press Frame (Fig. 1)

When a crack appeared in the frame of an old punch press (see Fig. 1), gas welding was selected over braze welding as the

repair method. All that was known of the base metal was that it was cast iron; it was assumed to be gray iron, probably of class 30 or 40.

When chipped out, the crack was 3 in. deep. It was enlarged to form a U-groove 4 in. deep with a 4-in. opening. The frame member was laid on its side and firmly braced, and the area near the weld zone was packed in fireclay (Fig. 1). The weld area was then preheated to 1200 F with a heating torch. Welding was done with a heavy-duty oxyacetylene torch fitted with a large welding tip, using cast iron filler metal and a carbon plate for backing. During welding, heat had to be applied from time to time to maintain an interpass temperature of about 1200 F. After welding, the frame member was stress relieved by being heated to 1200 F and held for 6 hr. Additional welding conditions are given in the table that accompanies Fig. 1.

Welding of Ductile Iron

Oxyacetylene welding is often used for the repair of defects in ductile iron castings. It has also been used successfully for hard facing of specific areas on castings for the purpose of increasing resistance to abrasion or corrosion (see Example 540 in the article on Hard Facing by Oxyacetylene Welding, in this volume). Oxyacetylene welding of ductile iron has been most successful using a ductile iron rod.

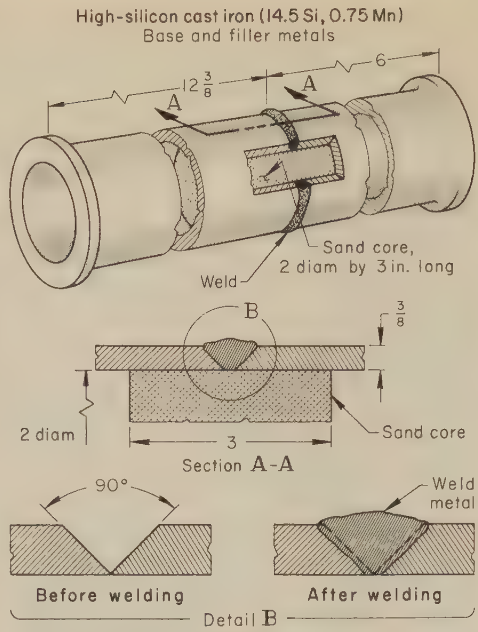
The repair of ductile iron castings is complicated by the fact that the only way to obtain graphite in nodular form in the weld deposit is to cause it to precipitate from the liquid in that form. Processes have been developed to cause nodularization by introducing magnesium or cerium, or both, into the weld zone by means of a special cast iron filler rod or a special flux. Filler metal RCI-B should be used for welding ductile iron.

Magnesium and cerium are carbide formers, and consequently must not be present in amounts beyond those required for nodularization. If these elements are present in excessive amounts, a postweld ferritizing anneal is necessary to restore ductility to the weld area; annealing reduces the strength of pearlitic irons and causes distortion of machined surfaces.

Joint preparation and joint cleanness require the same careful attention and the same procedures described earlier for welding gray iron. Preheating practice and interpass temperatures are essentially the same for welding ductile iron as those described in the foregoing for gray iron.

In welding ductile iron, a reducing flame should be used to minimize oxidation of the volatile nodularizing elements contained in both the base metal and the welding rod. The welding tip should be a type that produces a concentrated flame pattern. The weld area or the complete casting is first preheated to a dull red and flux is applied to the bottom of the weld groove. Heat is directed at the bottom of the weld groove until a puddle begins to form. Walls adjacent to the weld groove are then softened to blend into the puddle. It is recommended that the length of the molten puddle be limited to one inch.

A major problem in the welding of ductile iron is the complete loss of ductility in the heat-affected zone.



Filler metal	Same as base metal(a)
Flux	50% lime, 50% sodium bisulfite
Backing	Solid cylindrical sand core
Flame adjustment	Oxidizing
Welding position	Horizontal rolled
Number of passes	Two
Preheat	Furnace, 1600 F
Interpass temperature	1000 to 1650 F
Postheat	Furnace, 1600 F for 2 hr, furnace cool
Fixtures	Clamping jig, turning rolls

(a) Proprietary high-silicon cast iron containing 14.5% Si and 0.75% Mn

Fig. 2. Nonstandard length of corrosion-resistant high-silicon cast iron pipe that was fabricated by gas welding under conditions given in table (Example 530)

Welding of Malleable and White Irons

The effect of oxyacetylene welding on malleable iron is to create a wide heat-affected zone of white iron, the material from which the malleable iron was originally produced by applying a malleablizing heat treatment. Because of the hardness and brittleness of the white iron, base-metal properties are lost and the joint is prone to cracking. The hardened zones in either ferritic or pearlitic malleable iron can be reduced by annealing, but only by processing the casting through a special heat treating procedure for which the original foundry is best equipped.

Oxyacetylene welding is used in the foundry repair of small defects on rough castings. The repair is done while the casting is in the white iron condition, before malleablizing. White iron welding rods are used, which are cast by the foundry to match the base-metal composition, after allowing for constituent losses in deposition. Repair procedures are the same as for gray iron except that, after welding, the casting is given its normal malleablizing heat treatment.

Braze welding, using a copper alloy welding rod, is a more satisfactory method of obtaining relatively strong, machinable joints in malleable iron. Because the base metal is not melted in braze welding, peak temperatures are relatively low, and there is very little hardening in the heat-affected zone. Color match between the weld and the base metal is poor, however, and the service temperature of the casting is limited to about 500 F. Details of the process are given in the article on Oxyacetylene Braze Welding of Steel and Cast Irons, which begins on page 579 in this volume.

Gas metal-arc welding with bare-wire steel electrodes has been used in joining malleable iron where end uses do not require full base-metal strength properties. This process produces high peak temperatures, which are of short duration because of high welding speed. Heat-affected zones are therefore narrow. This process is discussed briefly on page 243 in the article on Arc Welding of Cast Irons, in this volume.

Welding of Corrosion-Resistant Cast Irons

Corrosion-resistant cast irons usually are identified as high-silicon, high-chromium or high-nickel irons, specifications for some of which permit welding for repair of minor casting defects. Weld deposits must usually duplicate base-metal compositions, but filler metals may not be generally available. The example that follows gives details of the special procedure that was successfully used by one manufacturer for assembly welding of corrosion-resistant high-silicon cast iron pipe.

Example 530. Assembly Welding of High-Silicon Cast Iron Pipe (Fig. 2)

High-silicon cast iron pipe, used for transporting liquids corrosive to steel, was normally manufactured in diameters ranging from 1 to 8 in. and in standard lengths of 3, 4 or 5 ft, depending on diameter. Standard pipe lengths were cast with beaded ends to permit coupling with split flanges, gaskets and bolts. Nonstandard lengths were made to order by welding together two pipe ends of suitable length. The manufacturer of this alloy iron found that a special gas welding procedure was the only practical method of obtaining a satisfactory weld.

Figure 2 shows the weld joint in an 18⅜-in. length of 2-in. pipe, normally supplied in 4-ft lengths. The sequence of operations for welding this pipe was as follows:

1. Grind both joint edges to 45° bevel.
2. Align parts in a clamping fixture and insert a 3-in.-long sand core to straddle the joint to be welded.
3. Preheat to 1600 F in a furnace.
4. Adjust oxyacetylene torch for oxidizing flame. (Extensive trials with reducing flames resulted in poor fusion and cracking, apparently because sufficiently high temperature could not be attained.)
5. Remove from furnace and tack weld in three places, using a high-silicon cast iron welding rod of the same composition as the base metal, together with a lime-base flux.
6. Place on turning rolls and weld in two passes, using the same rod and flux as for tacking. Place sheet insulation over the pipe, leaving opening over weld area for access. Maintain interpass temperature between 1000 and 1650 F.
7. Return to furnace for 2 hr at 1600 F; cool in the furnace with doors shut and burners off.
8. Inspect welds visually for cracks and other defects.
9. Test hydrostatically at 75 psi.

Welds produced by this method had the same corrosion resistance as the base metal. By welding special pipe lengths to order, inventory requirements were reduced and pattern alterations were avoided. Conditions for gas welding are given in the table with Fig. 2.

Hard Facing by Oxyacetylene Welding

*By the ASM Committee on Hard Facing**

OXYACETYLENE WELDING is used in many applications requiring build-up and hard facing. The welding equipment used is simple and versatile, and capital investment costs are low in comparison with those for arc welding. (For information on the use of arc welding for hard facing, including a comparison with the oxyacetylene process, see the article on Hard Facing by Arc Welding, page 152 in this volume, particularly Tables 3 and 4.)

Limitations. Hard facing by manual oxyacetylene welding requires a high degree of welder skill to obtain smooth, high-quality deposits, since both the welding rod and the torch flame have to be separately manipulated. The speed of welding is low compared with that of arc welding, and low deposition rates often preclude the use of oxyacetylene welding for hard facing applications on large components that require large quantities of facing alloy, unless automation of the operation is warranted by configuration of the surface and number of identical parts.

Major Applications. Oxyacetylene welding is best suited to hard facing applications in which the surface area to be faced is small. Thus, for facing steam valves, automotive and diesel-engine valves, cutter blades for wood and plastic, chain saw bars, and plowshares and other agricultural implements, it is often the most satisfactory process. It can be easily employed in the field. Broken edges on gear teeth, mismatched surfaces of machinery components, and parts made of nonferrous alloys, such as admiralty brass or Monel, can be built up with metal similar in composition to the base metal, or with a different metal.

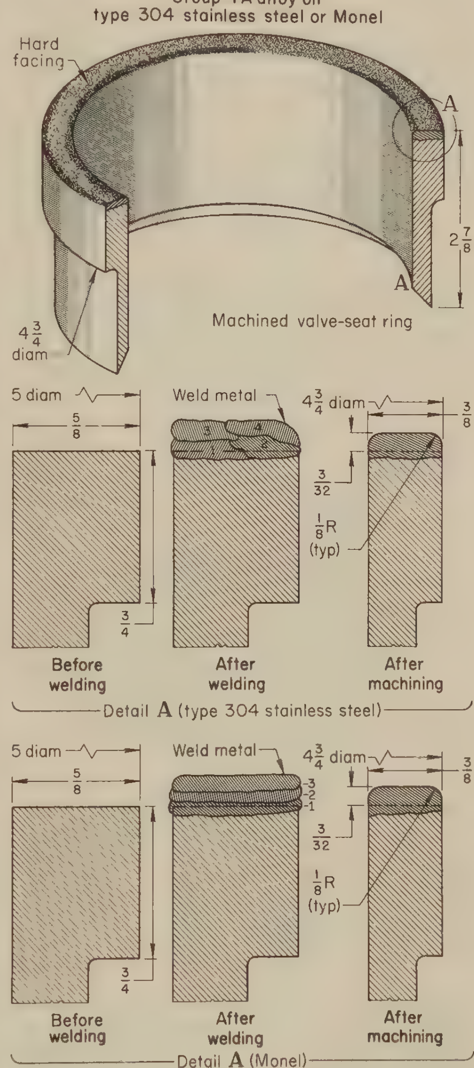
Principles of Operation

Supplies of oxygen and of acetylene, regulators, a welding torch, and welding rods are the primary requirements for hard facing by oxyacetylene welding. The factors that contribute to the success of the application are appropriate choices of gas mixture, gas pressure and velocity, and flame characteristics. The article on Gas Welding, page 565 in this volume, describes the equipment used for the control of these process variables.

Hard Facing Alloys

Most hard facing alloys can be applied by oxyacetylene welding. For the classification and compositions of these alloys, see Tables 1 and 2 in the article on Hard Facing by Arc Welding, which begins on page 152 in this volume. Choice of a specific alloy depends primarily on the application (see the article on Selection of Hard Facing Alloys, which begins on page 820 in Volume 1 of this Handbook).

Most hard facing alloys are available in different forms. Many of the more ductile alloys are available in the form of coiled wire. Those that are too brittle to coil are supplied as straight lengths of rod. Some alloys come in powder form and are applied by spraying, using a specially designed torch that incorporates a powder dispenser. Carbide materials are often supplied as granules contained in a metal tube (usually of low-carbon steel); the tube portion melts, thus acting as a matrix to embed the carbide on the work-metal surface.



Weld type	Hard facing
Thickness of hard facing overlay after machining	3/32 in.
Hard facing alloy	1/8 and 1/4-in.-diam 4A(a)
Gas pressure:	
Acetylene	5 psig
Oxygen	15 psig
Tip-orifice diameters	0.025 to 0.070 in.
Preheat	(b)

(a) Cobalt-base alloy with 28.5 Cr, 4.5 W, 3.0 Ni, 1.10 C. (b) For stainless steel rings, furnace preheat at 900 to 1000 F for 1 hr. For Monel rings, furnace preheat at 1150 to 1250 F for 1 hr, and torch heat at 1500 to 1650 F for no more than 30 minutes. Interpass temperature for Monel was 1500 to 1650 F.

Fig. 1. Valve-seat ring made of stainless steel or Monel, showing hard faced area, preweld dimensions, bead sequences and machined dimensions (Example 531)

Cleaning and Fluxing

Before the hard facing operation begins, the base-metal surfaces are thoroughly cleaned.

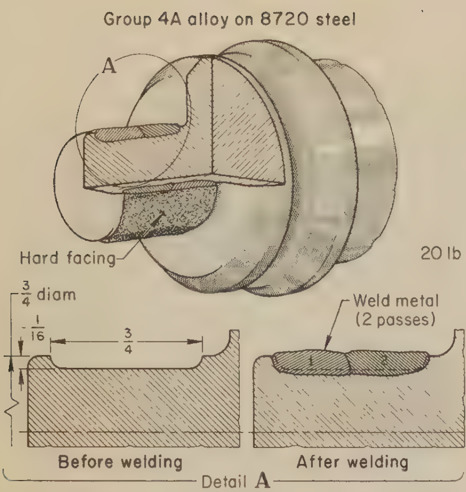
For hard facing of steel, a flux is seldom required if the surface is clean and dry, but flux may be required if the surface is contaminated and cannot be cleaned easily. For hard facing cast iron, a flux is commonly used.

If impurities are present on surfaces of the work metal, or if an excessive amount of oxide is produced in heating (usually, a neutral or reducing flame is used), it may be necessary to dislodge the solid contaminants by prodding or rubbing with the welding-rod tip. Oxide trapped beneath the hard facing overlay can react with carbon in the hard facing alloy to produce a gas and cause porosity. Hard facing alloys usually contain a deoxidizer that will control a moderate amount of oxidation.

Operating Procedures

Preheating (if used) is done after cleaning. The area of the workpiece to be hard faced is then heated to a red heat with the torch, even if preheating was used. For hard facing with cobalt-base alloys, the torch gas-inlet valves are adjusted to obtain an excess-acetylene flame having a blue envelope, or feather, about three times the length of the bright inner cone. This type of flame, called a "3×-feather" flame, is carburizing and helps to reduce oxides. It also adds carbon to the base-metal surface as the temperature rises, thereby lowering the melting point of the surface. For facing with nickel alloys, a neutral 2×-feather flame is commonly used. When melting begins, the surface glistens and appears watery, a condition known as "sweating". As soon as base-metal melting begins, a drop of the hard facing alloy (which has been preheated by the edge of the flame) is melted off. The drop will usually blend immediately with the sweating zone and will spread. More hard facing alloy is added as needed by melting drops from the rod, as the wetted area is carried forward by the heat of the flame. This procedure continues until the area to be hard faced is fully covered with hard facing alloy.

*For committee list, see page 152. Several of the examples in this article were contributed by members of other Metals Handbook welding committees.



Weld type	Hard facing
Thickness of hard facing overlay after grinding	1/16 in.
Hard facing alloy	1/4-in.-diam group 4A(a)
Gas pressure:	
Acetylene	15 psig
Oxygen	30 psig
Tip-orifice diameter	0.0935 in.
Oxygen flow	15 cfh
Preheat	600 F(b)
Production time	0.0599 hr per piece(c)
Cost Items	
Torch and related equipment	$95.00
Hard facing alloy, per pin	$0.47
Acetylene, per pin	$0.0041
Oxygen, per pin	$0.02

(a) Bare cast rod, 12 in. long. (b) Heating time was 2½ minutes, using natural-gas burners. (c) In lots of 100 pieces.

Fig. 2. Rotary rock-bit friction pin, showing hard faced areas on periphery (Example 532)

The procedure described in the preceding paragraph is subject to minor variations for particular applications.

Selection of hard facing alloy, gas mixture and flow rate, and operating procedure depends mainly on the base metal being hard faced, the properties and quality desired in the deposit, and the service conditions of the part. In the next example, a change in the base metal necessitated a change in hard facing procedure, although the same hard facing alloy was used.

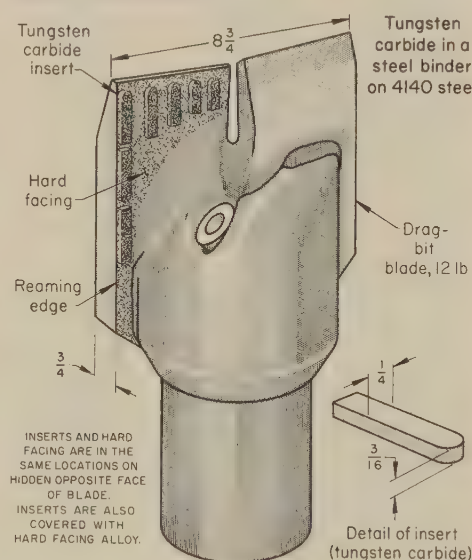
Example 531. Change in Hard Facing Procedure With Change in Base Metal From Stainless Steel to Monel (Fig. 1)

When made of type 304 austenitic stainless steel, valve-seat rings such as that shown in Fig. 1 were successfully hard faced with a cobalt-base group 4A alloy, using manual oxyacetylene welding and the procedure described below. When the valve-seat rings were made of Monel, the original procedure no longer produced acceptable deposits and had to be revised.

Type 304 Stainless Steel Rings. Valve-seat rings were machined, cleaned with acetone, preheated in a furnace at 900 to 1000 F for a minimum of 1 hr, and wire brushed before hard facing. A small area on the base-metal surface was then heated to the sweating condition, using a reducing flame. The temperature attained was high enough to ensure that sweating did not disappear when the torch tip was raised slightly. The end of the hard facing rod was then inserted into the flame and allowed to melt and flow over the sweating area. The first layer (tinning layer) was kept as thin as possible, and puddling was minimized to prevent excessive dilution with the base metal. At the end of each pass, the torch was raised with a spiral motion, which resulted in a heat gradient that allowed solidification to progress from the base metal to the surface of the deposited layer. At least two layers of hard facing alloy were applied to ensure a minimum thickness of 3/32 in. after machining. The two layers were applied in four passes, as shown in Fig. 1. Dilution of hard facing alloy with base metal was low, and liquid-penetrant tests indicated no weld cracking.

Monel Rings. When the procedure described for hard facing type 304 stainless steel valve-seat rings was used for Monel rings, difficulty was encountered in depositing the weld metal, porosity occurred in the hard facing, and the base metal cracked. The normal hard facing technique was unsuccessful because direct flame impingement (neutral or reducing) on the surface to be hard faced did not result in deposit flow. Therefore, the hard facing was deposited by using a slightly reducing flame to melt a drop of hard facing alloy onto the surface and then heating this puddle (rather than the surface) by direct contact with the hot inner cone of the flame throughout deposition. Hard facing alloy was fed to the puddle as rapidly as it would melt and flow. Three single-pass layers were deposited on the valve-seat ring, as shown in Fig. 1. After hard facing, the rings were cooled slowly in powdered asbestos.

Base-metal cracking was prevented by using preheating temperatures (1500 to 1650 F) that were higher than the hot-short range for Monel. Holding in this preheat range for no more than 30 minutes ensured against a decrease in room-temperature tensile properties.



Weld type	Hard facing
Thickness of hard facing overlay:	
Reaming edge	1/8 in.
Face of blade	1/16 in.
Hard facing alloy	Tungsten carbide tube metal(a)
Cast inserts	Tungsten carbide(b)
Gas pressure:	
Acetylene	15 psig
Oxygen	30 psig
Tip-orifice diameter	0.1285 in.
Preheat	900 F, or higher, in a furnace
Production rate	1.1 blades per man-hour
Cost Items(c)	
Torch and regulators	$250.00
Carbide inserts, per blade	$5.00
Tube metal, per blade	$7.00
Acetylene and oxygen, per blade	$2.65

(a) 60% tungsten carbide granules, 40% steel tube binder. (b) 4.0 to 4.5 C, 18.0 to 20.0 Co, 75.0 to 77.0 W. (c) Approximate.

Fig. 3. Two-way drag-bit blade, showing locations of hard facing overlay and cast inserts (Example 533)

The same torch tip-orifice sizes (0.025 to 0.070-in. diameter) were used for both procedures, but a 2× to 3×-feather flame was used for the stainless steel and a 1½× to 2×-feather flame for the Monel. Both stainless steel and Monel rings were inspected by the liquid-penetrant method after machining. Surfaces showing linear indications, or rounded indications more than 1/64 in. in diameter, were not acceptable. Additional processing details are given in the table with Fig. 1.

Manual Oxyacetylene Welding

Hard facing by manual oxyacetylene welding requires good coordination of rate of heat input and speed of welding, so that the flame can properly position and shape the weld bead. To obtain the temperature conditions needed for hard facing, preferential heating of the base metal or of the hard facing rod may be required. The welder must exercise control over the temperature at the weld zone, the deposition rate, and the nature and shape of the deposit. Several examples of hard facing using manual oxyacetylene welding are presented in this section.

Components of Oil-Field Equipment. The four examples that follow describe the successful application of hard facing to oil-field equipment components using manual oxyacetylene welding (see also Example 542, in which hard facing of rotary rock-bit bearings was mechanized).

Examples 532 to 535. Hard Facing of Parts for Oil-Field Equipment, Using Manual Oxyacetylene Welding

Example 532 — Rotary Rock-Bit Friction Pin (Fig. 2). Rotary rock-bit friction pins made of 8720 steel were coated with an abrasion-resistant hard facing alloy in accordance with the following procedure. A groove, 1/16 in. deep and 3/4 in. wide, was machined around the pin (see Fig. 2, Before welding), maintaining a 250-micro-in. or better surface finish on the machined areas. Next, the surface to be hard faced was washed with a solvent to remove cutting fluids and rust preventives. The pin was then preheated to 600 F in about 2½ minutes with natural-gas burners, and a hard facing of a group 4A alloy was applied to the groove, using a 3×-feather oxyacetylene flame and backhand welding. Additional processing details are given in the table that accompanies Fig. 2. Two passes were made and each bead was ended by overlapping the starting point, to allow trapped oxides to float to the surface where they could be removed by grinding. Upon completion of the hard facing operation, the pin was ground to finish dimensions, leaving a uniform deposit about 1/16 in. thick.

Example 533 — Two-Way Drag-Bit Blade (Fig. 3). Satisfactory service was obtained by hard facing of the two working surfaces on the blade of a 4140 steel drag bit with tungsten carbide tube metal, together with selective placement of cast tungsten carbide inserts, as shown in Fig. 3. Preparation for hard facing consisted in sand blasting all blade surfaces, machining the reaming edges, and preheating the blades by holding them in a furnace until a temperature of at least 900 F was attained. Welding of the inserts and hard facing alloy was done with an oxyacetylene torch equipped with a tip with a 0.1285-in. orifice. Inserts were attached by sweating them onto the surface of the blade. They and other areas of the blade, as shown in Fig. 3, were then covered with the hard facing alloy. The hard facing material was tungsten carbide granules contained in a steel tube. Tube size ranged from 1/4 to 1/8 in. in diameter. Postheating was not required.

Additional processing data and costs for equipment and consumable materials are given in the table that accompanies Fig. 3.

Example 534 — Blade-Type Stabilizer (Fig. 4). The three-blade stabilizer shown in Fig. 4, which is typical of many used in oil-field applications, was made by welding 1020 steel blades on a 4140 steel body and subsequently hard facing the surface of the blades as shown in Fig. 4. The number of blades on a stabilizer varied from three to six, and the length of the blades varied from 18 to 24 in.

Blades were prepared by machining to dimensions, welding onto the stabilizer body, and cleaning. Before hard facing, the stabilizer was preheated to 900 F, using natural-gas burners. The outer surface of each blade was hard faced with an overlay of 3/16 in. (max) of tungsten carbide tube metal (tungsten carbide granules in a steel tube), without flux, using an acetylene torch with a 0.1285-in.-diam tip orifice. Postheating was not required, and the blades were used as-surfaced, without further grinding or machining.

Additional processing conditions and approximate costs for equipment and consumables are given in the table that accompanies Fig. 4.

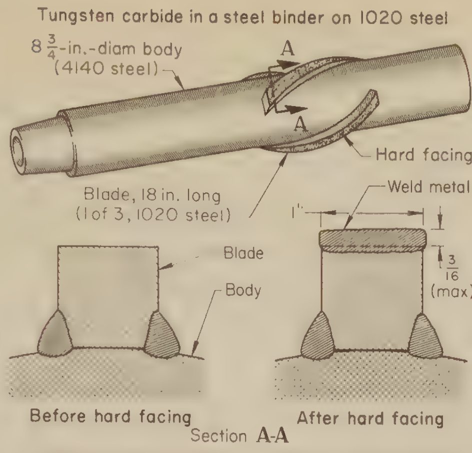
Example 535 — Junk Mill (Fig. 5). The 7¾-in.-diam junk mill shown in Fig. 5 is typical for the size range of about 3¼ to 8¾ in. in diameter. Some junk mills are much larger. Junk mills are used in oil-field operations for cutting up steel "junk" (broken and jammed tools in oil wells being drilled), and therefore it is mandatory that one side and the end of each cutting blade be hard faced to resist the extreme abrasion to which it will be subjected.

The mill shown in Fig. 5 was hard faced with tungsten carbide particles in a matrix of brass or nickel silver. Hard facing was done with an oxyacetylene torch equipped with a tip having an orifice diameter of 0.1285 in. The following processing steps were used:

1 The mill was placed in a fixture that would hold and rotate it for flat-position welding.
2 Areas to be hard faced were cleaned well.
3 A carbon mold block was clamped in position to prevent the hard facing alloy from running onto surfaces where it was not wanted.
4 The first blade was positioned. The whole area to be hard faced was preheated using a neutral flame and oscillating the flame. To remove surface oxide and inhibit oxide formation during welding, preheated surfaces were coated with a suitable flux.
5 Using a soft, neutral flame, flux-covered surfaces were pretinned with an overlay of about 1/16 in. of brass or nickel silver.
6 Employing the same neutral flame, and moving the flame evenly and smoothly over the entire surface, a group 5 (tungsten carbide) composite alloy was deposited on the pretinned surface. The composite alloy consisted of crushed tungsten carbide particles (particle size of ⅛ to ¼ in., classified by a screen) in a matrix of brass. The carbide particles were positioned while the deposit was still molten, care being taken to avoid directing the cone of the flame at the carbide particles.
7 Steps 3 to 6 were repeated for the remaining five blades.
8 The hot workpiece was wrapped in asbestos and permitted to cool slowly.

Other welding conditions, and costs for equipment and consumables, are given in the table that accompanies Fig. 5.

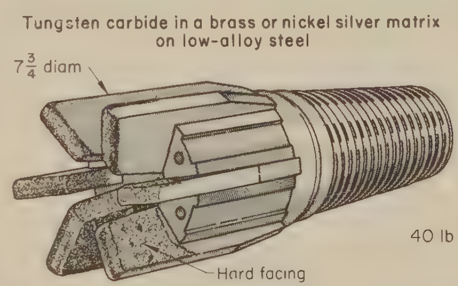
Engine Valves. Hard facing of the seating surfaces of engine valves (especially exhaust valves) by oxyacetylene welding is common practice. The process is used on new valves and for salvaging worn valves. It is applicable to relatively small valves, such as those used in small commercial engines, and to large diesel-engine valves that weigh more than 50 lb each. A procedure that proved successful for hard facing 1.892-in.-diam valves is described in the following example.



Weld type	Hard facing
Thickness of hard facing	3/16 in. max
Hard facing alloy	Tungsten carbide tube metal(a)
Gas pressure:	
Acetylene	15 psig
Oxygen	30 psig
Tip-orifice diameter	0.1285 in.
Preheat	900 F, with natural-gas burners
Production time	0.3 hr per linear foot(b)
Cost Items	
Torch and regulators	$250.00
Tube metal	$2.30(b)
Acetylene and oxygen	$0.80(b)

(a) 60% tungsten carbide granules, 40% steel tube binder. (b) Approximate, per linear foot for a 3/16-in.-thick, 1-in.-wide deposit.

Fig. 4. Three-blade stabilizer with tungsten carbide deposited on cutting blades (Example 534)



Weld type	Hard facing
Thickness of hard facing	About 1/16 in.
Hard facing alloy	Group 5(a)
Welding position	Flat
Gas pressure:	
Acetylene	15 psig
Oxygen	30 psig
Tip-orifice diameter	0.1285 in.
Preheat	300 F, with torch, using neutral flame
Production time	35 min per mill
Cost Items	
Welding equipment	$95.00
Hard facing alloy, per junk mill	$37.85
Oxygen, per junk mill	$0.20
Acetylene, per junk mill	$0.04

(a) Tungsten carbide in brass or nickel silver

Fig. 5. Junk mill that was hard faced on the wearing surfaces (Example 535)

Example 536. Use of Manual Oxyacetylene Welding for Rebuilding Engine-Valve Seats (Fig. 6)

The SAE EV 8 steel engine valve shown in Fig. 6 was grit blasted for removal of carbon deposits and dirt. The seat, which was to be hard faced, was then undercut in a lathe as shown in Fig. 6 (Before welding). The valve was placed on a special welding table that could be rotated by a power-driven mechanism controlled by a foot switch, and tilted for flat-position welding. The seat area of the valve head was preheated to 300 to 450 F by means of a gas torch. Using ¼-in.-diam rods of a group 4A alloy, a hard facing layer about ⅛ in. thick and ¼ in. wide was applied to the valve seat in two passes. After welding, the valves were submerged in a mica compound to ensure slow cooling. Additional processing details are given in the table that accompanies Fig. 6.

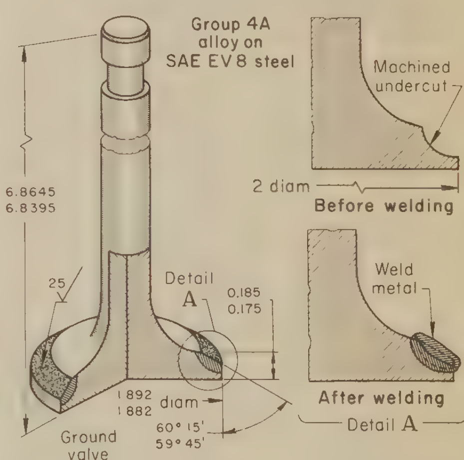
Average welding time was approximately 4 min per valve; machining before and after welding required 10 to 12 minutes. A pound of hard facing rod hard faced 20 to 25 valve seats. Cost of the special welding table was $65.

Dies and Punches for Hot Trimming. Hot trimming requires a material for the cutting edges of dies and punches that will retain its strength and sharpness at elevated temperature. Such edge properties are often obtained by hard facing, which frequently doubles the life of the die components and in some instances increases their life up to ten times. A procedure for hard facing trimming dies and punches is described in the example that follows.

Example 537. Hard Facing Edges of Hot Trimming Dies and Punches (Fig. 7)

The components shown in Fig. 7 (an A2 tool steel die and 4140 steel punch) were selectively hard faced with a group 4A alloy on the areas indicated. The hard facing alloy was applied manually with an oxyacetylene torch. A welding table and copper blocks were used to position parts for flat-position welding. The process was used on both new and worn components.

The surfaces to be hard faced were suitably grooved or recessed by milling, grinding, and boring, as required. The components were then furnace hardened and tempered to Rockwell C 45 to 50. No preheat was needed, but the surfaces to be hard faced were heated to sweating temperature by the torch used to deposit the hard facing alloy. A group 4A alloy was applied, using a 3× to 4×-feather flame. Deposit thickness varied from 1/16 to 7/32 in., depending on the thickness of the material to be trimmed and punched. After hard



Weld type	Hard facing
Thickness of hard facing	About ⅛ in. max
Hard facing alloy	Group 4A
Welding position	Flat
Preheat	300 to 450 F(a)
Production time	4 min per valve

(a) Smaller valves were heated only to ensure that moisture was removed from the surface.

The composition of SAE EV 8 is 0.53 C, 9.0 Mn, 21.0 Cr, 3.75 Ni. SAE EV 3 was also used for this type of valve; its composition is 0.20 C, 1.3 Mn, 21.0 Cr, 11.5 Ni.

Fig. 6. Engine valve that was rebuilt by hard facing the seating surface (Example 536)

facing, the surfaces were ground to close tolerances. About 12 hr was required to prepare, hard face, and finish machine one complete die set, consisting of punches, trimming die, and lower die.

The dies were used for hot trimming and punching forged track links. Service life of hard faced die components was as follows:

Die component	Number of track links
Trimming die	50,000
Small punches	15,000
Lower die	20,000
Oblong punch (not shown in Fig. 7)	30,000

About twice as many parts were trimmed and punched as would have been if die components had not been hard faced.

An application of manual hard facing for repairing cold work dies is described in Example 538.

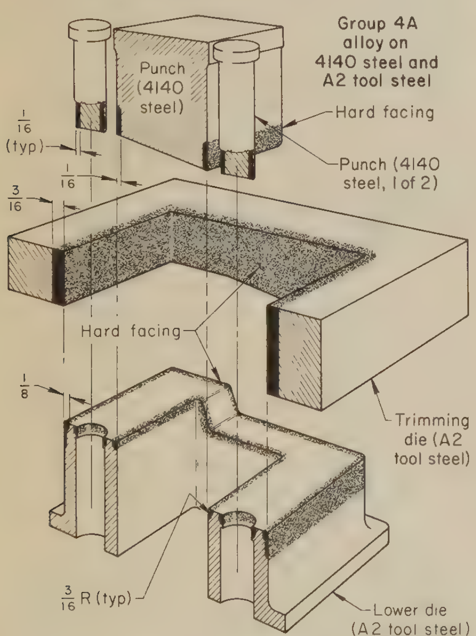
Powder Spraying

The use of an oxyacetylene torch equipped with a powder dispenser often increases the flexibility of hard facing by gas welding. The mixer section of the torch is constructed with an integral hopper for the alloy powder or a special opening into which is screwed a dispenser containing the alloy powder. Powder flow is initiated by depressing a lever on the torch handle, the powder being carried by the gases through the torch tip, where it is heated by the oxyacetylene flame.

Such a torch can be used with alloy powder alone or with powder and a hard facing rod, consecutively, or even simultaneously, as required, without stopping the operation. For filling a deep groove or a deep chipped area, common practice is to tin the area using the powder alloy, then to deposit the major portion of the hard facing alloy using an alloy rod (because it is faster), and to complete the deposit with the powder alloy. The rod and powder need not be of the same composition. When a thick deposit is required, the major portion can be laid with a rod that deposits a relatively tough metal, and the deposit can be completed by spraying on a thin layer of material of which 50% or more is tungsten carbide or another extremely hard material.

Powder spraying has proved especially advantageous in applications where a thin deposit is required (0.010 to 0.020 in. thick, for example). Powder spraying permits close control of deposit thickness, thus minimizing overdeposition, which wastes alloy and requires machining and grinding to remove the excess. Hard facing by powder-spray oxyacetylene welding is described in Examples 538, 539 and 540, in this article.

Repair of Cold Work Dies. Chipped edges of various types of cold work dies, including blanking dies, are commonly repaired by hard facing. Often this can be done without preheating or postheating the die, and therefore the die is out of service for a minimum length of time. The powder-spraying method of oxyacetylene welding described in the example that follows proved successful in one shop for repairing dies used for blanking sheet steel for automotive parts.



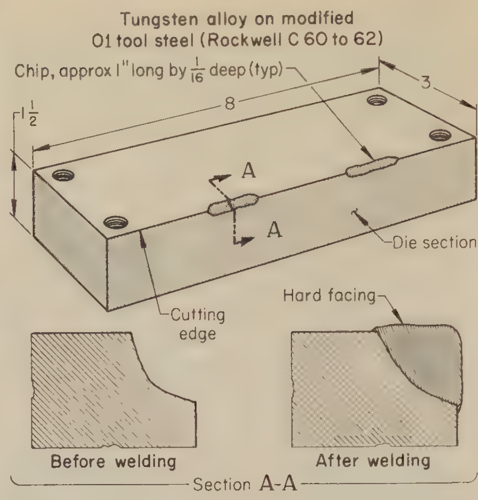
Weld type	Hard facing
Thickness of hard facing	1/16 to 7/32 in.
Hard facing alloy	Group 4A
Welding position	Flat
Gas flow:	
Acetylene	16 to 24 cfh
Oxygen	15 to 22 cfh
Preheat	(a)
Production time	12 hr per die set(b)

Cost Items

Hard facing alloy	6 to 7 lb at $6.12 per pound
Equipment for one welder	About $380(c)

(a) No preheat. Areas to be hard faced were heated to sweating temperature with the torch used to deposit the hard facing alloy. (b) Includes machining time. (c) For torch, regulators, hoses, tips, goggles, table and blocks.

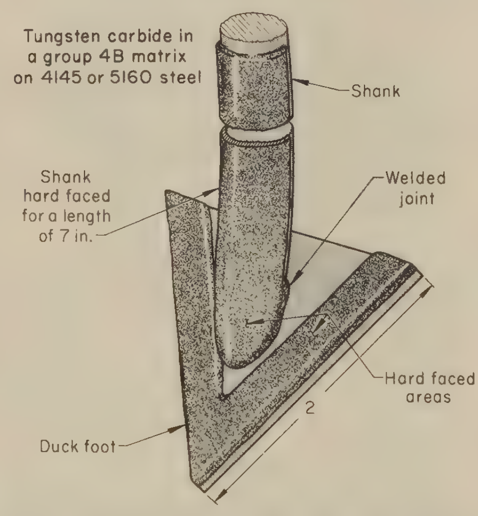
Fig. 7. Hot trimming dies and punches, showing hard faced areas (Example 537)



Weld type	Hard facing
Hard facing alloy	Proprietary powder(a)
Gas pressure:	
Acetylene	4 to 5 psig
Oxygen	25 to 30 psig
Preheat; postheat	None

(a) Tungsten carbide in a 4B alloy. Hand-fed rod was sometimes used in addition to powder.

Fig. 8. One section of an eight-section blanking die that was repaired by hard facing, using powder-spray oxyacetylene welding (Example 538)



Weld type	Hard facing; joining
Thickness of hard facing	0.020 to 0.030 in.
Hard facing alloy	Group 4B powder(a)
Welding position	Flat
Gas pressure:	
Acetylene	9 psig
Oxygen	22 psig
Preheat	600 F
Postheat	None
Production rate	One piece every 3 min(b)
Cost per piece (labor and material)	$1.50
Equipment cost, per welder	$450(c)

(a) Tungsten carbide was usually added (40 to 50%). (b) Includes welding duck foot to shank. (c) Approximate cost; includes torch, regulators, hoses and exhausts.

Fig. 9. Tillage tool used for introducing liquid ammonia into the soil. The operations included hard facing of the shank, and hard facing of the duck foot and welding it to the shank in a single operation. (Example 539)

Example 538. Powder-Spraying Method for Hard Facing Edges of Blanking Dies (Fig. 8)

Chipped cutting edges (Fig. 8) of dies used for blanking automotive parts from 11-gage (0.1196-in.-thick) low-carbon steel sheet were regularly repaired using a method based on feeding a powdered mixture of a nickel-base hard facing alloy and fine-mesh tungsten carbide through an oxyacetylene torch. Sometimes, for filling large chipped areas, additional hard facing alloy was hand fed from rod. The mixer part of the torch had an opening into which was screwed a moistureproof, bellows-type can containing the powdered alloy. A lever extending to the torch handle was depressed to start powder flow into the stream of oxyacetylene gas.

The work-metal surfaces were cleaned with a power-driven wire brush. The oxyacetylene torch was then adjusted for a neutral flame. The flame was played over the area to be welded until the surface reached a dull-red heat, and then it was concentrated momentarily on the starting area (keeping the torch in constant motion). The powder-dispensing lever was slowly depressed, and powder was distributed and fused over the weld area, to a height slightly above the die surfaces. The die section was cooled in air.

The weld deposit was ground flush with the die surfaces, and the die was returned to service without postheating. The hardness of the deposit ranged from Rockwell C 57 to 64.

Edges repaired by this procedure were quite satisfactory; they generally remained intact until the sections were ground below the repairs in resharpening.

Agricultural tools that are often hard faced include plowshares, disks, sweeps, and subsoil points of various types. The life of most of these tools can be prolonged by hard facing, but the cost of hard facing is high and cannot always be justified. For operation in some soils, such as those in Oklahoma and southern Kansas, tillage

tools must be hard faced for acceptable life. The extra cost of hard facing cannot be justified for tillage tools used in the less abrasive soils of the corn belt.

The example that follows describes an application where hard facing, using the powder-spraying method, increased the life of tillage tools by six to eight times.

Example 539. Hard Facing a Shank and a Duck Foot and Simultaneously Welding the Duck Foot to the Shank (Fig. 9)

To increase the life of the tillage tool shown in Fig. 9, which was used to introduce liquid ammonia fertilizer into the soil at a depth sufficient to avoid excessive evaporation, hard facing was applied to the leading surface of the shank and on the edges of the duck foot. The duck foot was welded to the shank in the same operation.

The components, of either 4145 steel or 5160 steel, were preheated to 600 F. First, the shank, which was the thicker of the two components, was heated with a powder-spraying-type torch to the hard facing temperature (judged by the welder). Then, the leading surface of the shank was hard faced for a distance of about 7 in. by spraying on a nickel-base alloy powder that contained 40 to 50% of tungsten carbide particles. The duck foot was heated and its edges were hard faced in a similar manner, and the foot was welded to the shank.

The hard faced tools lasted six to eight times longer than tools that were not hard faced, under the same service conditions. Other hard facing conditions are given in the table that accompanies Fig. 9.

Hard Facing of Cast Iron. Because of their relatively poor weldability, gray, malleable and ductile cast irons are hard faced less frequently than are steels, but the example that follows describes how a wear problem involving a ductile iron casting was solved by hard facing with a sprayed-on powder.

Example 540. Ductile Iron Castings Hard Faced on High-Wear Areas by the Powder-Spraying Method (Fig. 10)

Stone and sand thrown by the track of a crawler tractor caused severe wear on a 10-sq-in. area of a ductile iron transmission housing (see Fig. 10). This area was sometimes worn through after a few months of operation.

Three different methods of protecting the high-wear area were tried. The first method was to cover the vulnerable area with a hardened steel plate secured by bolting, but this was unsatisfactory because the bolt heads were mutilated beyond use in a short time. A second approach was to hard face the surface by arc welding. Several different hard facing alloys were tried, but application of the hard facing alloy was too slow, and concern over the possible propagation of cracks into the base metal from weld checks was a deterrent. The third approach was to spray the vulnerable area with a powdered mixture of nickel-base alloy and tungsten carbide through an oxyacetylene torch. This method was simple and rapid.

Equipment cost was moderate. Although the alloy and carbide powders were expensive, only 1½ oz was needed to deposit a typical overlay ranging from 0.010 to 0.030 in. thick. This hard faced layer did not separate from the base metal when tested by striking with a ball-peen hammer, and proved to be satisfactory in service. Micrographs showed no adverse effects on the ductile iron microstructure at the interface between the hard facing and the base metal. This fact was attributed to the relatively low peak temperature involved.

Before welding, the area to be hard faced was marked off, and surface oxide was removed by grinding. The general area was then locally preheated, using the oxyacetylene torch. A light coating of metal powder was deposited over the area and was heated until the surface was uniformly wetted. Additional metal powder was then applied to build up the hard facing layer to an average thickness of about 0.020 in.

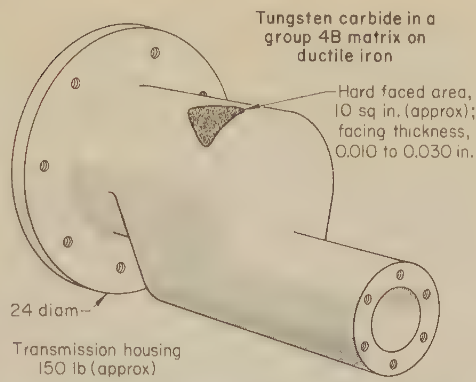


Fig. 10. Drop-housing portion of the transmission on a crawler tractor, showing area subjected to severe wear from stones and sand cast off by the track (Example 540)

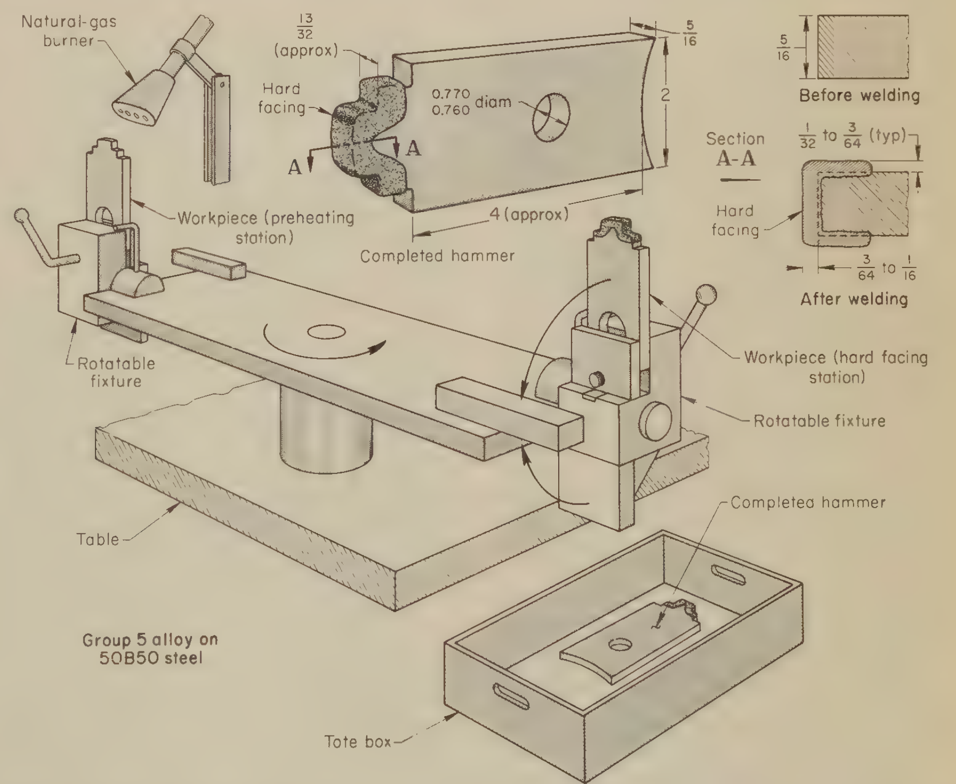
Mechanized Handling of Workpieces

For repetitive work, various types of mechanized handling and workholding devices are used. The two examples in this section describe and illustrate relatively simple mechanisms used for production hard facing.

Feed-Mill Hammers. In new equipment, feed-mill hammers are supplied in the heat treated condition or hard faced. Because of the severely abrasive conditions of service, a hard faced hammer can have a life eight times as long as that of a heat treated hammer, and often the user will hard face hammers before they are put in service, if they were purchased unfaced in the heat treated condition. A procedure for production hard facing of feed-mill hammers is described in the example that follows.

Example 541. Use of Rotating and Swiveling Fixtures for Production Hard Facing of Hammers (Fig. 11)

The feed-mill hammer shown in Fig. 11, made from annealed 50B50 steel, was hard faced with a tungsten carbide composite (group 5 alloy). All surfaces of the hammer were milled before hard facing, to ensure a clean, scale-free surface, and the machined hammer was straightened. It was then hard faced by means of the two-station setup shown in Fig. 11. This setup enabled the operator to preheat one hammer while he was hard facing another. A simple swivel arrangement brought the preheated hammer to the hard facing station, where the fixture was rotated for flat-position welding. After hard facing, the hammer was released from the fixture and



Welding Conditions

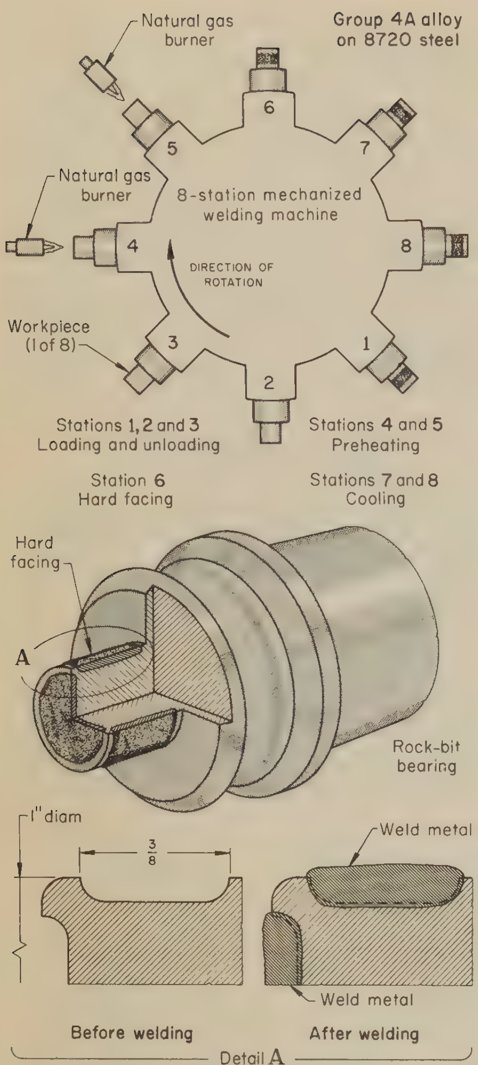
Weld type	Hard facing
Thickness of hard facing	1/32 to 1/16 in.
Hard facing alloy	Group 5(a)
Gas flow:	
Acetylene	44 to 56 cfh
Oxygen	43 to 54 cfh
Preheat	1000 to 1200 F
Postweld heat treatment	Furnace harden and temper to Rockwell C 50 to 56
Production rate	One hammer every 1.48 minutes; 2.96 minutes total preheating and hard facing time

Cost Items

Welding torch, preheat burner, regulators, fixtures, piping and accessories	$400.00
Hard facing alloy, per pound	$3.25
Hard facing alloy and gases, per hammer	$0.062

(a) Tube metal rod (1/8 in. in diameter by 14 in. long) contained 3.7 to 4% carbon and a minimum of 60% tungsten carbide; amount of rod used per hammer was about 0.0075 lb.

Fig. 11. Feed-mill hammer, and setup for preheating and hard facing it (Example 541)



Weld type	Hard facing
Thickness of hard facing	$\frac{3}{32}$ to $\frac{1}{8}$ in.
Hard facing alloy	$\frac{5}{16}$-in.-diam group 4A(a)
Gas flow:	
Acetylene	15 cfh
Oxygen	12 cfh
Preheat	1000 to 1200 F
Finishing operation	Grinding

(a) Cobalt-base alloy with 24 to 28 Cr, 12 to 15 W, 10 Fe max, 3.0 to 3.5 C, 0.5 to 1.0 Si

Fig. 12. (Upper) Plan view of an eight-station rotary holding device for mechanized hard facing. (Lower) Rotary rock-bit bearing and areas to be hard faced, before and after welding. (Example 542)

dropped into a tote box. The empty fixture was then loaded with another hammer and moved to the preheating station.

The hard facing operation was completed in 1.48 min, and therefore the distance between the preheating torch and a hammer had to be such that a hammer would be preheated to the correct temperature in the same length of time.

Other hard facing details are given in the table that accompanies Fig. 11.

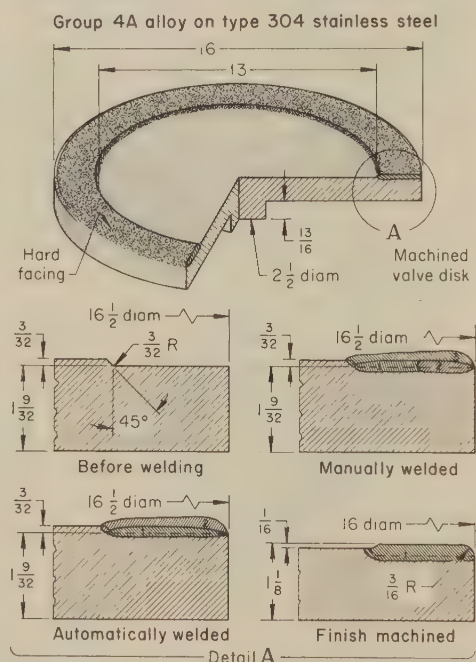
Rotary rock-bit components are subjected to extremely severe service conditions. They often operate several thousand feet underground, and because much time is required to change tools, every effort is made to prolong their life. Hard facing the wearing surfaces with a cobalt-base alloy (such as one of the group 4A alloys) has proved effective in prolonging their life. A manual procedure for this operation is described in Example 532. A mechanized procedure is described in the example that follows.

Example 542. Hard Facing Rotary Rock-Bit Bearings in a Mechanized Setup (Fig. 12)

Rotary rock-bit bearings, such as the one shown in Fig. 12, were hard faced in production quantities by means of the equipment shown schematically in Fig. 12. Mechanization was justified when annual production exceeded 50,000 bearings.

The mechanized welding machine consisted of a rotating table on which eight fixtures for holding and rotating bearings were mounted. Around the table were eight stations for loading, preheating, hard facing, cooling and unloading bearings.

Each bearing was machined to the typical dimensions given in Fig. 12 (Before welding) and thoroughly cleaned. To begin the hard facing sequence, four fixtures were loaded with bearings. The first bearing was preheated to 1000 to 1200 F at stations 4 and 5 by natural-gas burners. It was then moved into position in front of the operator at the hard facing station. The torch used for hard facing was manipulated manually. When hard facing was completed, the table was rotated to the next position, thereby placing another preheated bearing in position to be hard faced, and advancing the hard faced bearing to a cooling station. After the first hard faced bearing had moved through cooling stations 7 and 8, it was removed from the turntable and replaced by a bearing to be preheated and hard faced.



Weld type	Hard facing
Thickness of hard facing	$\frac{5}{32}$ in. min
Hard facing alloy	$\frac{5}{16}$-in.-diam group 4A(a)
Welding position	Flat
Gas pressure:	
Acetylene	12 psig
Oxygen	60 psig
Torch tip sizes:	
Preheating	0.040-in.-diam orifice, $\frac{9}{16}$ in. long
Sweating	0.040-in.-diam orifice, $\frac{13}{16}$ in. long
Hard facing	0.0465-in.-diam orifice, $\frac{15}{16}$ in. long
Preheat	800 to 1000 F
Cooling method	Cool slowly in powdered asbestos
Inspection	Liquid penetrant(b)

(a) Cobalt-base alloy with 28.5 Cr, 4.5 W, 3.0 Ni max, 1.10 C. (b) After final machining. No linear indications, and no rounded indications more than $\frac{3}{32}$ in. in diameter, were permitted.

Fig. 13. Gate-valve disk that was hard faced in an automatic setup (Example 543)

Additional details of the hard facing step of the mechanized procedure are given in the table that accompanies Fig. 12.

Automatic Hard Facing

Hard facing by oxyacetylene welding can be completely automatic, which means that the workpieces are mechanically fed and rotated under a hard facing torch that is mechanically held and manipulated. Configuration of the surface and quantity of identical parts to be hard faced are the principal factors that determine whether it is practical to automate the process. In some applications, the configuration of the surface to be hard faced is so complex that mechanical manipulation of the torch is not practical, regardless of production quantities. An application in which automatic hard facing proved advantageous is described in the example that follows.

Example 543. Gate-Valve Disks Hard Faced by Automatic Welding (Fig. 13)

When type 304 stainless steel gate-valve disks were automatically hard faced with a group 4A alloy, the time required for welding was reduced from 100 to 40 minutes, and the number of layers, from three to two, as compared with manual welding. However, the automatic method could be used only when a lower hardness and poorer quality could be tolerated. The manual technique used was essentially the same as described for the valve seat in Example 531.

Using the automatic method, the workpiece was rotated, and hard facing was done in the flat position. Four torches were used: two for preheating, one for bringing the workpiece surface to the sweating temperature, and one for hard facing. For preheating, the flame was adjusted to neutral; for bringing the workpiece to the sweating temperature, a reducing flame was used (2× to 3× feather); and for melting the hard facing rod, the flame was again neutral. The two preheating torches provided supplemental heat, and were separately supported on a stand. The torches used for sweating and hard facing were oscillated to ensure a uniform deposit.

The hard facing alloy (in rod form) was fed by gravity. The rods were positioned vertically by guides attached to the oscillator, but were allowed to rest on the work surface.

The workpiece was prepared by machining, cleaning with acetone, preheating in a furnace at 800 to 1000 F, and brushing with a wire brush.

The hard facing deposit was built up in two layers. The first layer was kept as thin as possible and puddling was minimized to prevent excessive dilution with the base metal. Following the automatic welding, the deposit was drawn out with a hand-held torch and filler metal was added as required to avoid shrinkage at the termination of the weld and to ensure cleanup in the final machining operation. After hard facing, the disks were buried in powdered asbestos and permitted to cool slowly.

Quality was checked by liquid-penetrant inspection. No linear indications, and no rounded indications more than $\frac{3}{32}$ in. in diameter, were allowed in accepted welds.

Qualification of the procedure required that one sample piece, at least 8 in. in diameter by 4 in. thick, be hard faced, and four sections be cut from it for liquid penetrant inspection, hardness testing (Rockwell C 38 min), and microscopic examination of cross sections at a magnification of 40. Each section was required to be free of cracks, incomplete fusion, linear defects, and porosity greater than 0.015 in. in diameter.

Additional hard facing details are given in the table that accompanies Fig. 13.

BRAZING

CONTENTS

Furnace Brazing of Steel

*By the ASM Committee on Brazing of Steel**

FURNACE BRAZING is a mass-production process for joining the components of small assemblies by a metallurgical bond, using a nonferrous filler metal as the bonding material and a furnace as the heat source. Furnace brazing is feasible only if the filler metal can be preplaced on the joint before brazing and retained in position during brazing. This article describes the application of furnace brazing to the joining of carbon and low-alloy steels, usually with a copper filler metal and occasionally with a silver alloy filler metal. Furnace brazing of other metals is dealt with in individual articles in this volume.

Furnace brazing requires the use of a suitable atmosphere to protect the steel assemblies against oxidation, or oxidation and decarburization, during brazing and during cooling, which is accomplished in chambers adjacent to the brazing furnace. The proper brazing atmosphere also makes possible the proper wetting of the joint surfaces by the molten copper filler metal, usually without use of a brazing flux (Example 557 describes an exception).

Although filler metals other than copper can be used in furnace brazing carbon and low-alloy steels, copper is generally preferred because of its low cost and the high strength of the joints produced. The high brazing temperature necessary when copper filler metals are used (2000 to 2100 F) is also advantageous when steel assemblies are to be heat treated after brazing.

Applicability

In general, the steel assemblies that are brazed most efficiently and economically are small and weigh less than 5 lb. Much larger assemblies can be brazed in specially built furnaces; the size of assemblies is limited by the heat required to bring them to the brazing temperature. Most steel assemblies are brazed at 2000 to 2100 F. This temperature, which is considerably higher than those employed in the heat treatment of steel, imposes limitations on furnace design and operation, including the maximum feasible size of the heating chamber, the degree of tightness and temperature uniformity that can be maintained, the time required to heat the workpieces to the brazing temperature, and the weight of loads that can be supported at 2000 F without sagging of furnace fixtures.

Among the steel components that are commonly furnace brazed are machined parts, light stampings, deep drawn sheet-metal parts, small forgings, and some castings. Usually, components are designed to be "self-jigging" — that is, capable of being assembled for brazing without the use of fixtures. Fixtures are sometimes required, but are avoided whenever possible; they add weight and change in dimensions after repeated exposure to elevated temperature. Among the many methods used to ensure adequate assembly for brazing are staking, expanding, spinning, swaging, knurling, crimping, press fitting, and tack welding. These, and other methods, are discussed in detail in the section on Assembly for Brazing, pages 603 to 607.

Advantages. The principal advantage of furnace brazing over other brazing processes is that it permits the use of a variety of prepared protective atmospheres, notably the rich exothermic-base, the endothermic-base, and some nitrogen-base atmospheres. These atmospheres are among the least expensive; they can be generated in the plant in large volume; they provide excellent protection against oxidation; and they can be prepared with any carbon potential in the range of about 0.2% to more than 1.0% C, depending on the atmosphere. This range of carbon potential is sufficient to accommodate all carbon and low-alloy steels, including those carburized before brazing. By selecting an atmosphere with a carbon potential that matches the carbon content of the work metal, brazing can be accomplished without carburizing or decarburizing the work metal.

Because the protective atmospheres used for furnace brazing are suffi-

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John B. Given, Advisory Engineer, Advanced Process Development, International Business Machines Corp.; C. F. Heckel, Material and Process Engineer, National Cash Register Co.; S. Maszy (retired), formerly Chief, Materials Application, Martin Company Div., Martin-Marietta Corp.; W. P. McQuillan (deceased), formerly Central Laboratories, Westinghouse Electric Corp.

Q. D. Mehrkam, Vice President, Research & Development, Ajax Electric Co.; R. Leon Shelton, Welding Engineer, Transmission and Chassis Div., Ford Motor Co.; H. M. Webber, Manager, Process Engineering, Harper Electric Furnace Corp.; J. R. Wirt (retired), formerly Delco-Remy Div., General Motors Corp.

Some of the examples presented in this article were contributed by members of other Metals Handbook welding and brazing committees.

ciently reducing to iron oxide, they usually eliminate the need for fluxes when brazing carbon steel with copper filler metal. These atmospheres can reduce light oxide films present on the surfaces of workpieces at the time of entry into the furnace, and they can prevent any further oxidation of the surfaces during the brazing cycle. An oxide-free surface normally promotes ready wetting of the workpiece by the molten filler metal. However, some low-alloy steels that contain a total of more than 2 or 3% of chromium, manganese, aluminum and silicon form more stable surface oxides, and they require highly reducing atmospheres (such as dry hydrogen or dissociated ammonia), a flux, or nickel plating to obtain adequate wetting action.

Another major advantage of furnace brazing is its ability to process large quantities of assemblies at low unit cost on either a batch or continuous basis. Furnace brazing is most efficient and economical when used in mass production, but it is sufficiently flexible to handle occasional small loads and low-production items, although at a higher unit cost.

Furnace brazing sometimes replaces another brazing process to increase the production rate. For instance, masonry drills of the type shown in Fig. 1 were initially assembled by induction brazing the sintered carbide tip to the low-alloy steel body, using a silver alloy filler metal. A slot was milled in the cutting end of the drill body to receive the sintered carbide tip with a light press fit. When it became necessary to produce these drills in larger quantities, furnace brazing was selected to replace induction brazing. The press fit used for induction brazing was found to be adequate to hold the drill body and carbide tip in position during furnace brazing, but the filler metal was changed to a copper paste slurry into which the tips were dipped before assembly. The drills were carried through the brazing furnace on a mesh-belt conveyor at a speed adjusted to give maximum penetration of the filler metal. Brazing was at 2030 to 2050 F, and production rate was 1000 to 1100 3⁄16-in.-diam drills per hour and 500 to 600 5⁄8-in.-diam drills per hour.

Furnace brazing can provide close temperature control and uniformity at all stages of the brazing cycle, including cooling. It can provide atmospheric protection during both heating and cooling. It can provide a different protective atmosphere in different chambers or compartments of the furnace, although this is rarely done. Also, furnaces of special design make it possible to braze in a controlled vacuum, although this is seldom done in brazing carbon and low-alloy steels.

Furnace brazing provides a uniform distribution of heat in the mating parts of the joint at the brazing temperature. However, if the difference in sectional thickness of the parts to be brazed is great, it is sometimes necessary to preheat them to just below the melting point of the filler metal, soak them until the heat is equalized, and then increase the temperature to the brazing range. If joint design and fit are satisfactory, and the correct amount and form of filler metal is provided, brazed joints are uniformly strong and sound. Several joints on the same assembly can be brazed in a single operation. With proper atmospheric protection, the brazed assemblies that leave the furnace cooling chamber (at about 300 F) are clean and bright, requiring no cleaning.

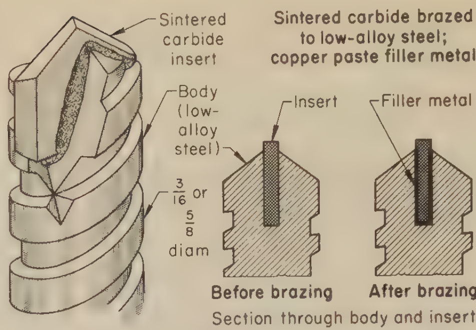


Fig. 1. Masonry drill with carbide tip that was furnace brazed to drill body to meet high production requirements

Limitations. Most of the limitations of furnace brazing are directly related to the high temperatures required to braze with copper filler metal. These temperatures exceed the average brazing temperature required to braze with silver alloy filler metals by 500 F or more. They are high enough to cause grain coarsening in medium-carbon, high-carbon and low-alloy steels; however, grain refinement can be obtained by subsequent heat treatment. The high brazing temperatures adversely affect the life of furnace components, especially those components that are exposed to the maximum temperature, such as furnace linings, electrical heating elements, muffles, rails, trays and conveyor belts.

The initial cost of a furnace and atmosphere generator is high, compared with that of most other types of brazing equipment. For this reason, the purchase of furnace brazing equipment cannot be justified for a new project if production quantities are low, and another brazing method may have to be considered. However, if a brazing furnace is already available, a few assemblies can be brazed economically.

Generator-prepared atmospheres may contain toxic compounds. Those that have a total of 5% or more of combustible gases (H_2, CO and CH_4) constitute a potential fire and explosion hazard. Safe operating practice and preventive maintenance of furnaces, generators and venting systems are mandatory (see the Appendix on Safe Operation of Brazing Furnaces, which begins on page 614).

Most of the disadvantages related to the life of furnace components have been lessened by improvements in furnace design and materials. For example, the average life of a refractory brick lining in a modern copper brazing furnace is about five years. The life of a high-temperature alloy muffle in a gas-fired furnace is about one year.

Sequence of Operations

Furnace brazing entails four processing operations: cleaning, assembling and fixturing, brazing, and cooling.

Cleaning is generally limited to the removal of oils used in machining operations. The preferred cleaning methods are alkaline cleaning, solvent cleaning, and vapor degreasing. When alkaline cleaning is used, it is important that all alkaline compounds be removed from workpieces before they enter the brazing furnace. Pigmented drawing compounds containing lead are generally removed by mechanical cleaning methods, such as dry grit blasting or wet blasting with an abrasive slurry. If they are not completely removed, drawing compounds containing lead are extremely detrimental to the quality of the brazed joint and to the life of furnace components.

Assembling and Fixturing. Components to be furnace brazed are generally designed for assembling by press fitting, expanding, swaging, or other means that eliminate the need for fixtures. However, fixtures are occasionally required for holding parts in proper relationship or for positioning an assembly in the brazing furnace so that the molten filler metal flows in the required direction.

The cleaned components are assembled with filler metal applied within or adjacent to the joints to be brazed. Assemblies are then loaded onto trays for batch-type or roller-hearth continuous furnace brazing or are transferred directly to the conveyor for mesh-belt conveyorized furnace brazing.

Brazing. The assemblies are moved into the brazing chamber of the furnace, where they are heated under a suitable protective atmosphere. When the assembly reaches a temperature higher than the melting point of the filler metal, the filler metal wets and flows over the steel surfaces and is drawn into the joints by capillary action. In making the bond, the filler metal forms a solid solution with, but does not melt, the steel surface. Heating time for furnace brazing most steel assemblies is from 10 to 15 min.

Cooling. The assemblies are moved to the cooling chamber of the furnace, where they are cooled under a protective atmosphere (usually the same atmosphere as was used in the brazing chamber). They remain in the cooling chamber until they have cooled enough so that they will not discolor when exposed to air — usually to about 300 F.

Summary of Operating Conditions. Table 1 is a summary of the conditions for furnace brazing that were employed in 29 of the 30 examples of commercial practice presented in this article. Table 1 identifies the assembly by name, lists the steels being brazed, the method of assembly, the filler metal, the type of furnace used, the protective atmosphere, the furnace temperature and heating time, and the production rate.

Brazing Furnaces

The furnaces most often used in the furnace brazing of steel assemblies are box furnaces, mesh-belt conveyor furnaces, and roller-hearth conveyor furnaces. All three types can be gas fired or heated by electricity, but for copper brazing at 2050 F, the roller-hearth type is usually electric. Gas-fired braz-

Table 1. Summary of Furnace Brazing Conditions Employed in Applications Described in Examples in This Article

Example number	Name of assembly	Base metal	Method of assembly	Filler metal	Type of furnace	Protective atmosphere	Furnace temperature, F	Heating time, minutes	Assemblies brazed per hour
544	Pivot shaft	12L14 to 1213 steel	Interference fit	BCu-1a(a)	Pusher(b)	Exothermic	2050	12	120
545	Gear and ring	9310 steel	Interference fit	BCu-1a(a)	Batch(c)	Hydrogen(d)	2050	30	...
546	Cam	1010 to 1215 steel	Sliding fit	BCu-1	Conveyor(e)	Endothermic	2070	11	1000
548	Cam and sleeve	1113 to 1020 steel	Staking	BCu-1	Pusher(b)	(f)	2050	15	60
549	Block and arm	1215 to 1010 steel	Tack welding	BCu-1a(a)	Conveyor(e)	Endothermic	2070	9	900
550	Plate and stud	1215 to 1010 steel	Sliding fit	Cu plating	Conveyor(e)	Endothermic	2070	8	2200
551	Hub and lever	12L14 to 1020 steel	Interference fit	Cu plating	Pusher(b)	(f)	2050	10	400
552	Type wheel	1010 to 1213 steel	Staking	BCu-1a(a)	Conveyor(e)	Endothermic	2050	(g)	125
553	Shaft to arm	12L14 to 1095 steel	Interference fit	BCu-1a(a)	Conveyor(e)	Dissoc ammonia	2050	(h)	1200(j)
554	Boss and cylinder	1012 to 1010 steel	Staking	BCu-1	Conveyor(e)	Endothermic	2040	11	250
555	Multiple cam	1010 to 1215 steel	Staking	BCu-1, -1a(a)	Conveyor(e)	Endothermic	2070	10	500
556	Contact to bracket	Tungsten to l-c steel	Fixturing	BCu-1	Conveyor(e)	(k)	2050	6	1200
557	Propeller blade	4350 steel	Fixturing	BCu-1(m)	Conveyor(n)	(p)	2080	50	...
558	Arm, cam, collar	1010 to 1215 steel	Sliding fit	BCu-1	Conveyor(e)	Endothermic	2070	12	250
559	Arm, hub, stud	1010 to 1215 steel	Interference fit	BCu-1	Conveyor(e)	Endothermic	2070	9	1750
560	Shaft and plate	(q)	Riveting	BCu-1	Pusher(b)	(f)	2050	15	150
561	Multiple gear	1010 to 1215 steel	Interference fit	BCu-1	Conveyor(e)	Endothermic	2070	10	3500
562	Bellows housing	Brass to steel	Interference fit	BAg-1a(r)	Box(b)	Endothermic	1350(s)	10	180
563	Manifold	1008 to 1020 steel	Fixturing	Silver alloy(t)	Conveyor(e)	Dissoc ammonia	1600(s)	12	60
564	Insecticide bomb	1010 to 1113 steel	Interference fit	BCu-1	Conveyor(u)	Exothermic	2100	12	702(v)
565	Tube and lever	Low-carbon steel	Staking	BCu-1	Conveyor(e)	Exothermic	2000-2010	...	...
566	Can-opener blade	Low-carbon steel	Staking	BCu-1	Conveyor(e)	Exothermic	2000-2010	...	...
567	Plate and bushing	Low-carbon steel	Fixturing	BCu-1	Conveyor(e)	Exothermic	2000-2010	...	...
568	Throttle linkage	12L14 to 1010 steel	Interference fit	BCu-1a(a)	Conveyor(e)	Endothermic	2100	10	548
569	Valve stem	1117 steel	Interference fit	BCu-1	Box(b)	Exothermic	2050	12	1560
570	Pump-nozzle holder	1117 steel	Interference fit	BCu-1	Box(b)	Exothermic	2050	...	1500
571	Stop plate	1117 steel	Interference fit	BCu-1	Box(b)	Exothermic	2050	12	1500
572	Tappet shell	1118 steel	Interference fit	BCu-1	Box(b)	Exothermic	2050	15	800
573	Valve	1113 steel	Interference fit	BCu-1	Box(b)	Exothermic	2050	...	...

(a) Paste. (b) Electric. (c) Gas-fired. (d) Dew point, —70 F. (e) Mesh-belt. (f) 30% CO, 16% H_2, rem N_2. (g) Total cycle time, ½ hr. (h) Belt speed, 6 in. per minute. (j) Preparation rate was 400 assemblies per hour. (k) Endothermic: 20% CO, 40% H_2, 40% N_2; dew point, +65 F. (m) High-temperature brazing flux was used. (n) Circular. (p) 10 to 12% CO, 10 to 14% H_2, rem N_2; dew point, —9 F. (q) Low-carbon steel to leaded low-carbon steel. (r) Flux was AWS type 3A. (s) Furnace temperature was considerably higher than flow-point temperature of filler metal to provide accelerated heating. (t) 75% Ag, 22% Cu, 3% Zn. (u) Roller-hearth. (v) For each of two furnaces used.

ing furnaces require the presence of a heat-resisting alloy muffle in the heating chamber to prevent the products of combustion from contaminating the protective atmosphere. Electric furnaces are usually operated without a muffle, and thus avoid the baffling of heat and the sometimes reduced production that may be encountered with a muffle, as well as the costs of maintaining and replacing the muffle. All furnaces must be sufficiently gastight to contain a protective atmosphere.

Furnace Ratings. The capacity of a brazing furnace is generally expressed in terms of gross weight of work load processed per hour. Trays, fixtures and conveyor belts are included in gross weight and are estimated to be about one-third of the total work load. Thus, a furnace with a gross-weight capacity of 150 lb per hour can be expected to process about 100 lb of assemblies per hour. Ratings are based on copper brazing of steel assemblies at a maximum temperature of 2100 F.

Box Furnaces. A box-type brazing furnace that is heated by electricity is shown schematically in Fig. 2. It consists of a heating chamber and a water-jacketed cooling chamber that is at least three times as long as the working length of the heating chamber. In standard models, the working length of the heating chamber ranges from 26 to 36 in.; the length of the cooling chamber ranges from 84 to 114 in. Door openings are 8-by-8 in. to 18-by-18 in. The brazing atmosphere, which is supplied by a generator (not shown in Fig. 2), is maintained within both the heating and cooling chambers. Throat baffle doors, which are normally closed, serve to increase effective heating length and to reduce end losses. Sliding doors at the entrance and exit of the furnace, also normally closed, help to maintain the protective atmosphere inside the furnace at high purity and to reduce the loss of atmosphere. The end doors are equipped with automatic gas-flame curtains.

The refractory-brick walls and roof of the heating chamber are backed up with thermal insulation. The load-carrying hearth plates are made of a heat-resisting alloy, silicon carbide, or alumina. Side rails (not shown in Fig. 2) serve to guide trays and to protect sidewall heating elements. The heating elements under the hearth plates and on the sidewall and roof are spaced to ensure temperature uniformity and are regulated by thermocouples.

The brazing atmosphere is fed to both heating and cooling chambers through inlets located outside the exit baffle door. Gas flow is manually set and is measured by a flowmeter. An inlet for purging gas is located inside the heating chamber to provide gas for "burnout". A protective-atmosphere venting system is not usually required with box-type furnaces, because the entrance and exit doors are never opened at the same time, thus avoiding contamination of the atmosphere by a through draft of air.

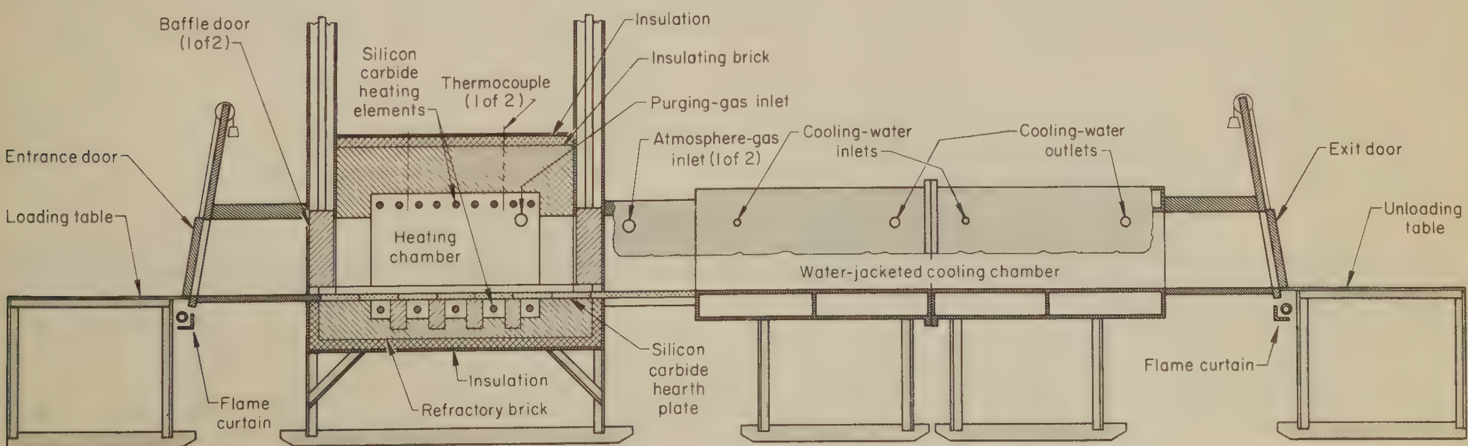


Fig. 2. Box-type brazing furnace with a water-jacketed cooling chamber

The cooling chamber is constructed in one or more segments, which are joined together and to the heating chamber by welding or by bolting with gaskets at interconnecting flanges, to provide a gastight seal. Each segment is equipped with its own water-cooling system, thereby providing maximum control of cooling from zone to zone. The temperature of the cooling water is thermostatically controlled, to minimize water consumption and to avoid condensation in liners during furnace idling. (When work is resumed, condensed moisture could turn to steam and cause oxidation of steel parts.)

Typically, such a furnace will accommodate four trays at a time: one in the heating chamber and three in the cooling chamber. As soon as the tray in the heating chamber reaches brazing temperature, the operator pulls the end tray out of the cooling chamber and pulls the other two trays closer to the end. He then pushes the hot tray of brazed assemblies into the empty space in the cooling chamber, and pushes a new tray of unbrazed assemblies into the heating chamber.

Mesh-belt conveyor furnaces offer the advantages of continuous operation at high capacity, and accurate, automatic cycle timing in both the heating and cooling chambers. An electrically heated, mesh-belt conveyor furnace, incorporating several special features, is shown in Fig. 3. Standard models of this furnace are made with mesh-belt widths ranging from 6 to 36 in. and hearth areas of up to 33 sq ft. Large-diameter (24 in. or more) drive and idler pulleys and flat return plates prevent sharp or reverse bends in the belt, thus extending belt life. The drive and pinch rolls are rubber faced. The belt take-up is a catenary loop at the driving end of the conveyor, which allows up to 4 ft of belt stretch before the belt has to be shortened. This take-up mechanism produces minimum tension on the belt, and allows the belt to contract automatically when the furnace is shut down. The belt is driven by an electric motor equipped with a variable-speed control and located under the loading area. Several wrought stainless steels, including type 314, are satisfactory belting materials.

The construction of the heating chamber, including the brickwork, is similar to that of a box furnace. Refractory-lined baffle doors, such as those shown on the box furnace of Fig. 2, can also be installed. These are manually adjusted to the precise height of the work load or to close the throats completely during standby. The height of the end doors can also be adjusted to reduce the consumption of protective atmosphere and to aid in directing atmosphere flow. The exit door is equipped with a flame curtain. As with the box furnace, brazing atmosphere is fed to both the heating and cooling chambers through inlets located outside the heating-chamber exit baffle. The control of brazing-atmosphere flow is described in the subsequent section on Venting for Mesh-Belt Conveyor Furnaces. The cooling chamber is similar to that of a box furnace.

Heating chambers of mesh-belt conveyor furnaces commonly range in length from about 2 to 12 ft; cooling chambers are at least three times as long. Representative ratings for copper brazing of steel assemblies are 120 to 1200 lb of assemblies per hour.

Roller-hearth conveyor furnaces are continuous furnaces in which the conveyor consists of driven rolls made of a heat-resisting alloy. The ends of the rolls extend through the sidewalls of the heating and cooling chambers, where they are held in suitable bearings and are rotated by sprockets and an endless chain controlled by a variable-speed driving mechanism.

Roller-hearth furnaces are generally used for high production, particularly when loading density or height of assemblies is considerably above average. Some furnaces have door openings up to 30 in. high, requiring the use of purging chambers preceding the heating chambers to prevent contamination of the brazing atmosphere.

Assemblies to be brazed can be loaded directly on the roll table, if they are long enough, but more commonly they are loaded on flexible trays made of a wrought or cast heat-resisting alloy. Trays range from 30 to 36 in. long and from 18 to 30 in. wide.

There is virtually no limit to the length of the heating and cooling chambers in roller-hearth furnaces. Typical production rates range from 350 to 2000 lb of brazed assemblies per hour. Extra-long furnaces have produced up to 3700 lb of assemblies per hour.

Furnace Idling. When a copper brazing furnace is to be idle for only one shift, the temperature is reduced to about 1800 F and the flow of brazing atmosphere is maintained. For idling over a longer period, a temperature of 1400 to 1600 F is satisfactory. When the furnace contains a flammable atmosphere, it may be purged, either by the burnout method or by the introduction of nonflammable gas. At the end of the idling period, the purging operation is reversed and the flammable atmosphere is reintroduced into the furnace. Methods of purging, including the burnout method, are discussed in the Appendix on Safe Operation of Brazing Furnaces, beginning on page 614.

Venting for Mesh-Belt Conveyor Furnaces

Proper venting of mesh-belt brazing furnaces is of prime importance in avoiding discoloration or decarburization of assemblies because of contamination from infiltrating air, air or moisture contained in assemblies, gas flame curtains, and volatilized oil from unclean components, and in preventing the contaminants from drifting in the wrong direction through the heating and cooling chambers. A venting system of poor design can counteract the beneficial effects of the brazing atmosphere. In general, the brazing atmosphere should flow toward the ends of the furnace. With this flow pattern, the atmosphere flows *counter* to the work in the heating chamber, sweeping air and contaminants from the entrance, and it flows *with* the work in the cooling chamber, providing protection up to the point of exit.

Drafts. The direction of room drafts often corresponds to the direction of the wind outside, particularly if doors and windows are open. Sometimes, large baffles are installed across the ends of furnaces to block or deflect room drafts. Exhaust hoods with stacks are mounted at the furnace ends over the door openings, to reduce drafts further and to carry away the hot products of combustion. Also, the input flow of brazing atmosphere at various points in the furnace can be adjusted to meet the demands of the moment. Because all of these techniques for draft control are subject to failure, properly designed exhaust hoods and ductwork systems are needed.

Poor Design for Venting. Typical of poor venting design is the system shown in Fig. 4(a). Stacks from exhaust hoods at the entrance and exit ends of the furnace go directly out through the plant roof, and have no

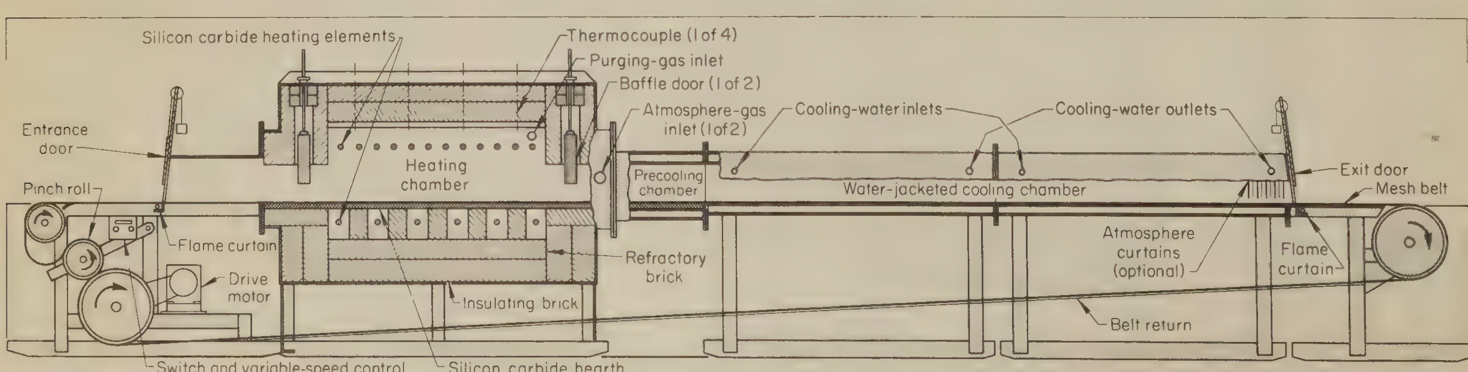


Fig. 3. Mesh-belt conveyor brazing furnace with a water-jacketed cooling chamber

dampers for adjustment of draft. Because winds blowing over the top of one stack do not necessarily travel with the same velocity over the top of the other stack, there is a difference in the amount of suction in the two stacks. Also, the differential velocities can reverse from hour to hour, and this can affect the direction or velocity of flow of brazing atmosphere through the furnace. Because the stacks are connected directly to the hoods, downdrafts can blow air into the heating and cooling chambers, contaminating the brazing atmosphere and disrupting temperature uniformity. In addition, the hoods are located over the tops of door openings only, leaving the sides and bottoms unprotected, and they are therefore ineffective in blocking room drafts, although this is their intended function.

Effective Venting. A successful venting system is shown in Fig. 4(b). With this system, the exhaust hoods feed into open collectors with dampers, not directly into stacks. The collectors draw in room air along with the hot products of combustion, which helps to cool the stacks and to minimize downdrafts. Ducts from the collectors lead to a single stack through the roof, which, with or without an exhaust fan and depending on the room height and the amount of natural draft, prevents variations in stack draft. The dampers permit adjustment of stack draft to control the direction of flow of brazing atmosphere through the entire furnace, ensuring that this flow is outward toward the end doors. This provides maximum protection and minimum contamination in the heating and cooling chambers.

Adjustable end doors are another feature that contributes to successful operation of the venting system shown in Fig. 4(b). The end doors are lowered so that they are as close to the tops of the workpieces as possible to reduce air infiltration and to minimize atmosphere consumption. Raising the door at one end of the furnace slightly higher than that at the other end creates a draft or chimney action, which also counterbalances room drafts.

As shown in Fig. 4(b), the door at the entrance end (left) is set higher than that at the discharge end (right), and the damper in the collector at left is farther open than that at the right. This encourages maximum counterflow of the brazing atmosphere, which enters the furnace at the hot end of the cooling chamber. The atmosphere is preheated by the outgoing hot workpieces and, after passing through the heating chamber, forces air and other contaminants out through the entrance door. If a room draft is flowing mildly in this same counterflow direction, air can infiltrate the cooling chamber with adverse effects. To counteract this condition, the damper and end door at the exit end are opened and those at the entrance end are partially closed. This counterbalances the room draft and still provides a rate of flow of brazing atmosphere out of the entrance end. Unless the venting system is subjected to extremely strong room drafts, the design in Fig. 4(b) affords complete control of the flow of atmosphere through the furnace in either direction.

Protective Furnace Atmospheres

The gas atmospheres used in furnace brazing serve primarily to protect the steel assemblies from oxidation or scaling and to assist the flow of filler metal by promoting wetting of steel surfaces. Both functions require a gas atmosphere that is reducing. When required, the atmosphere may also serve to maintain the carbon content of the steel, by preventing carburization or decarburization at elevated temperatures. To satisfy all requirements, the atmosphere must provide complete protection to assemblies in both the heating and the cooling chambers of the brazing furnace.

Rich Exothermic-Base Atmosphere. In theory, almost any reducing atmosphere can be used in furnace brazing of low-carbon steel with a copper filler metal. In practice, a rich exothermic atmosphere is usually selected, because it is the least expensive of the generated atmospheres, is adequately reducing, has relatively low sooting potential compared with drier atmospheres containing more carbon monoxide, and requires a minimum of generator maintenance.

The content of reducing gases in a rich exothermic atmosphere (12.5 to 15% H_2 and about 11% CO) usually is sufficient to promote good wetting and to maintain bright surfaces on steel assemblies. When hydrogen is low and moisture is high, refrigeration of the gas to reduce its dew point is required to ensure bright surfaces.

The carbon potential of the atmosphere is normally low (about 0.10% C), but it can be increased to about 0.40% C by decreasing the dew point and removing the carbon dioxide. Such a modification is seldom required, because the initial carbon content of the steel assemblies to be brazed is low (0.10 to 0.18% C) or because superficial decarburization can be tolerated. When control of carbon potential is required, a rich endothermic atmosphere usually is preferred.

The nominal composition of a rich exothermic-base atmosphere is given in Table 2. This atmosphere is produced by partial combustion of a hydrocarbon fuel, such as natural gas or propane, in air, using a generator that is equipped to control the ratio of air to fuel gas and thus to produce the desired composition. Detailed information regarding the generation of a rich exothermic atmosphere and the generator equipment employed is given on pages 71 to 73 in the article on Furnace Atmospheres, in Volume 2 of this Handbook.

For the application described in the following example, either an exothermic or an endothermic atmosphere would have been satisfactory; an exothermic atmosphere was selected, primarily because it was less expensive.

Example 544. Cost Advantage of an Exothermic Atmosphere in Copper Brazing of Low-Carbon Steel (Fig. 5)

The 12L14 steel pivot arm and the 1213 steel shaft that comprised the assembly shown in Fig. 5 could have been copper brazed in either an exothermic atmosphere or an endothermic atmosphere, with satis-

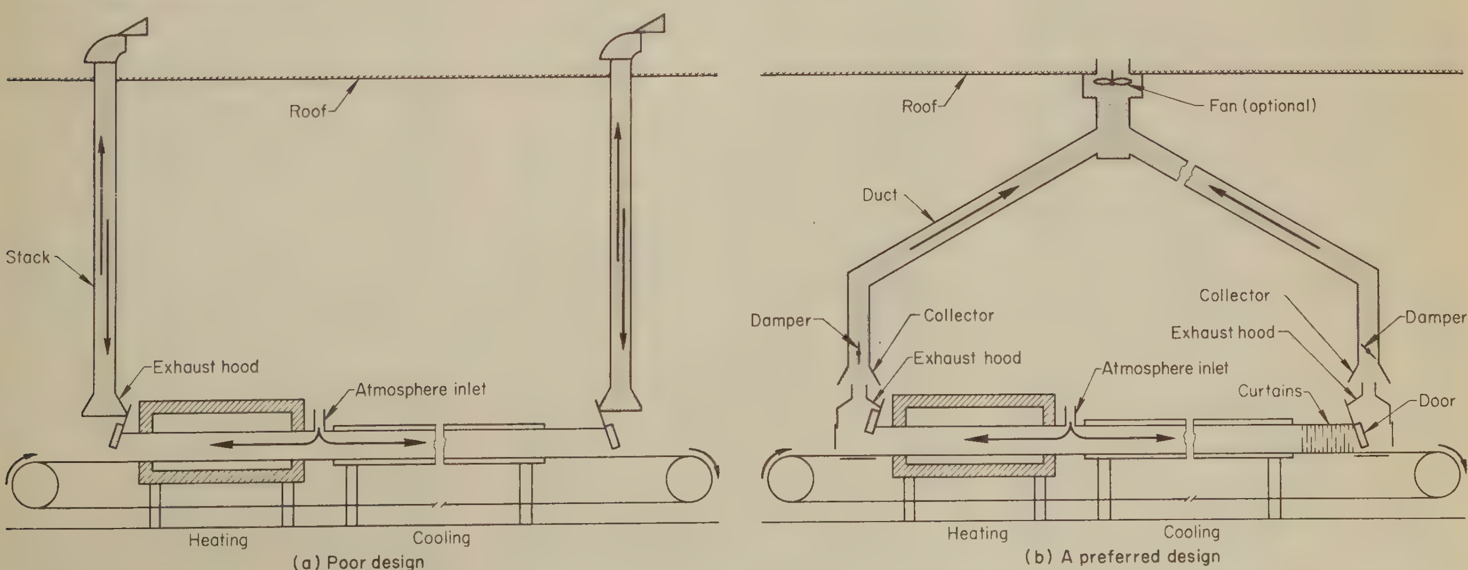


Fig. 4. Venting systems for mesh-belt conveyor furnaces, showing (a) *a poor design and* (b) *a preferred design*

Table 2. Protective Atmospheres Commonly Used in Furnace Brazing

AGA class	Description	Nominal composition, % by volume: N_2	CO	CO_2	H_2	CH_4	Dew point, F	Fuel required, cu ft(a)	Air-gas ratio(b)
102	Rich exothermic-base	71.5	10.5	5.0	12.5	0.5	(c)	155	6.0
...	Products of combustion of hydrocarbon gas passed through incandescent charcoal	Rem	30.0	...	16.0	...	−15	80	6.0
202	Rich prepared nitrogen-base	75.3	11.0	...	13.2	0.5	−40	160	6.0
301	Lean endothermic-base	45.1	19.6	0.4	34.6	0.3	+20 to 50	190(d)	2.6
302	Rich endothermic-base	39.8	20.7	...	38.7	0.8	+25 to −5	200(d)	2.5
601	Dissociated ammonia	25.0	...	...	75.0	...	−60	(e)	...
...	Hydrogen, purified	...	...	...	100.0	...	−75	...	...

(a) Per 1000 cu ft of atmosphere; based on use of natural gas rated at 1000 Btu per cubic foot. For other fuel gases, multiply by: 2.0, for high-hydrogen artificial gas; 2.5, for medium-hydrogen, high-CO artificial gas; 0.4, for propane; and 0.3, for butane. (b) Values indicate number of parts of air to one part of gas (based on use of natural gas at 1000 Btu per cubic foot). (c) Dew point is about 10 F above temperature of cooling water; dew point may be reduced to +40 F by refrigeration, or to −50 F by adsorbent-tower dehydration. (d) Plus 250 cu ft per 1000 cu ft for heating gas. (e) 23.5 lb of ammonia per 1000 cu ft of atmosphere.

factory results in terms of both the quality of brazed joint and the metallurgical and surface condition of the steels after brazing. Consequently, the decision to use an exothermic atmosphere was based solely on the desire to reduce cost.

The initial cost of an endothermic generator with a capacity of 500 cu ft per hour was \$5665, whereas the cost of an exothermic generator of similar capacity was only \$3110. The cost of producing 1000 cu ft of gas was \$0.20 to \$0.25 for the endothermic gas and \$0.08 to \$0.12 for the exothermic gas, based on \$0.60 per 1000 cubic feet for natural gas, \$0.01 per kilowatt-hour for electricity, and \$0.10 per 1000 gallons for cooling water.

The pivot arm and shaft were degreased prior to assembly. Copper filler metal was applied in the form of a paste, as shown in Fig. 5. Assemblies were brazed at 2050 F under an exothermic atmosphere in an electric pusher-type furnace. Time in the brazing heat was 12 min, and production rate was 120 assemblies per hour.

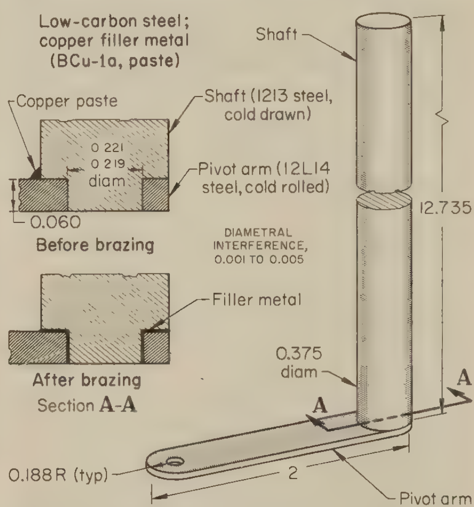


Fig. 5. Pivot-arm-and-shaft assembly that was furnace brazed in an exothermic atmosphere, rather than in an equally suitable endothermic atmosphere, to save atmosphere generator and production cost (Example 544)

Products of Combustion Through Charcoal. This brazing atmosphere, which was used in the application described in Example 551, is made by passing an exothermic gas (product of combustion of air and a hydrocarbon) through incandescent charcoal (see Table 2). The result is a gas having a low dew point (−15 F) and a higher carbon potential than the rich exothermic-base atmosphere.

Rich Prepared Nitrogen-Base Atmosphere. Although a rich exothermic-base atmosphere is most widely used in copper brazing of low-carbon steel, it is much less versatile than a rich prepared nitrogen-base atmosphere (AGA class 202). Because of its low dew point (−40 F) and the absence of carbon dioxide, this nitrogen-base atmosphere is more reducing than, and does not exhibit the decarburizing effects of, an unpurified exothermic atmosphere. It can be used whenever decarburization of steel assemblies is not permissible; hence it is used to protect carbon and low-alloy steels of medium carbon content. It is likely to cause partial decarburization of high-carbon steel and to carburize low-carbon steel. It is effective in protecting low-carbon steel from oxidation.

The nominal composition of a rich prepared nitrogen-base atmosphere is given in Table 2. A nitrogen-base atmosphere generator incorporating a scrubbing system is described on pages 74 and 75 in Volume 2 of this Handbook. The cost per unit volume of a prepared nitrogen-base atmosphere is roughly double that of an exothermic atmosphere. However, the main economic disadvantage lies in the high initial cost of generating and scrubbing equipment.

Endothermic-Base Atmospheres. The nominal compositions of a lean (AGA class 301) and of a rich (AGA class 302) endothermic-base atmosphere are given in Table 2. A lean atmosphere is generated by reacting lean mixtures of hydrocarbon gas and air in an externally heated chamber in the presence of a nickel catalyst.

By controlling the dew point of endothermic-base atmospheres, their carbon potential can be accurately controlled in the range from 0.20 to 1.30% C, making it possible to ensure equilibrium conditions for carbon and low-alloy steels of low, medium and high carbon content, thereby avoiding carburization and decarburization. The atmospheres are reducing, and thus protect against oxidation and promote wetting during brazing.

Generators for producing these atmospheres are considerably less complicated and less expensive than those required for producing nitrogen-base atmospheres; the operating costs for generating the gases are roughly equivalent. Endothermic-atmosphere generators and the reactions obtained in them with several different hydrocarbon fuels are described on pages 75 to 78 in Volume 2 of this Handbook, in the article on Furnace Atmospheres.

The principal disadvantages of endothermic atmospheres are their potential explosiveness when mixed with air and their sooting potential when dry, at the temperatures encountered in the cooling chambers of brazing furnaces.

Other Atmospheres and Vacuum. Other, more expensive atmospheres and vacuum are also suitable for the furnace brazing of steel. Because of the stability of surface oxides containing chromium, manganese, titanium, vanadium, aluminum and silicon, alloy steels containing a total of more than 2 or 3% of these elements can be fluxless brazed satisfactorily only in vacuum or in one of the strongly reducing atmospheres, such as dissociated ammonia or purified dry hydrogen (see Table 2 for compositions). Failure to reduce these alloy-containing surface oxides completely will prevent the filler metal from flowing in the joint, and so a flux may be necessary. Nickel or copper plating sometimes helps to prevent oxidation and improves wetting.

The more expensive atmospheres are rarely used without special justification, although in some plants that require them for brazing nonferrous alloys or for use in heat treating, they may be used for brazing steel simply because they are available and because justification for installing another atmosphere generator is lacking. In Example 545, a dry hydrogen atmosphere was used, and in Examples 553 and 563, dissociated ammonia was used.

Brazing With Copper Filler Metals

Copper is the preferred filler metal for furnace brazing of carbon and low-alloy steel assemblies without flux in reducing protective atmospheres. Significant amounts of two trace elements, arsenic and phosphorus, should be avoided, because they form brittle compounds in the brazed joint. The copper should be essentially free of arsenic, and if it was deoxidized with phosphorus, the residual phosphorus content should be low.

Filler Metals and Forms. There are three standard copper brazing filler metals, bearing the AWS designations BCu-1, BCu-1a, and BCu-2 (Table 3).

BCu-1 filler metal contains a minimum of 99.90% copper and a maximum of 0.10% of other elements. It is available in the form of strip, rod, and wire on spools.

BCu-1a filler metal contains a minimum of 99.0% copper and a maximum of 0.30% of other metallic elements. It is available as a powder in two standard sieve analyses, medium-1 and medium-2. It is applied as a powder in some applications, but is frequently mixed with a liquid vehicle and applied as a paste. In most applications, BCu-1 and BCu-1a are interchangeable.

BCu-2 filler metal is available in the form of a paste and contains a minimum of 86.5% copper and a maximum of 0.50% other metallics and 1.3% nonmetallic contaminants, including chlorides, sulfates, and matter insoluble

in nitric acid or soluble in acetone. The remainder is oxide. The paste is a suspension of particles of copper and cuprous oxide in a volatile vehicle.

Various proprietary pastes, identified by trade name and not covered by an AWS specification, are available commercially. These pastes are prepared with several different types of hygroscopic and nonhygroscopic vehicles, with different thinning, drying and spattering characteristics. In addition to the vehicle, some contain commercially pure copper powder only, and others contain powdered cuprous oxide only. Some pastes contain mixtures of copper powder and cuprous oxide; of copper powder, cuprous oxide and iron oxide; or of copper powder, cuprous oxide and iron powder. In general, pastes containing oxides require strongly reducing atmospheres to promote flow. Pastes containing iron or iron oxide are intended to fill joint clearances up to about 0.003 in. at brazing temperature.

The unalloyed copper filler metals (BCu types) should not be confused with the copper-phosphorus (BCuP) filler metals, which are never used for joining steel, or with the copper-zinc (RBCuZn) filler metals, which generally require the use of a borax – boric acid flux.

Joint Strength. A principal advantage of the copper filler metals used in the furnace brazing of steel is the high strength they impart to the brazed joints. The shear strength of copper joints in low-carbon steel generally ranges from 22,000 to about 31,000 psi, while the tensile strength ranges from 25,000 to almost 50,000 psi. The rotating-beam fatigue strength of these joints is also high; in one series of tests, copper brazed joints in low-carbon steel withstood 10 million cycles without fracture at stresses of about 12,000 psi. In all tests of joint strength, it is apparent that fit affects strength. When other variables are constant, a diametral interference fit of 0.001 in. will be slightly stronger than a slight diametral clearance fit (such as 0.0005 in.), and a diametral interference fit of 0.002 in. generally will be stronger still. Joint clearances and joint strength are discussed in greater detail in the section on Joint Fit and Design.

Carburizing of Copper Brazed Assemblies. The liquidus temperature of the copper filler metals is about 1980 F, and the recommended temperature range for brazing is 2000 to 2100 F. This range is safely above the temperature ranges for austenitizing and carburizing of carbon and low-alloy steels. Gas carburizing temperatures seldom exceed 1725 F. Carburizing a steel assembly after copper brazing, as was done in the following example, has no adverse effect on the brazed joint.

Example 545. Use of Copper Filler Metal To Braze a Steel Assembly That Was Later Carburized and Hardened (Fig. 6)

The components of the gear and clutch-ring assembly shown in Fig. 6 were joined by copper brazing, and were subsequently carburized and hardened. They were made of 9310 steel, and were brazed in a dry (−70 F dew point) hydrogen atmosphere because of the relatively high chromium content (1.00 to 1.40%) of the steel. The hydrogen atmosphere, which ensured the reduction of chromium-containing oxides on the surfaces to be brazed, was introduced at the top of a retort and exhausted through a sand seal at a rate of 15 retort volumes per hour. The retort was heated to the brazing temperature (2050 F) in a gas-fired batch furnace and was cooled in air to room temperature before the assemblies were removed. The filler metal was a paste made from copper powder (BCu-1a), and the brazing time was 30 min.

Preparation for brazing consisted in machining the mating surfaces of the joint to a light interference fit and blasting with cast iron grit.

After being brazed, the gear and clutch-ring assembly was gas carburized in a continuous furnace, using standard procedures, and hardened. Each assembly was then put through torque proof-testing.

Table 3. Copper Filler Metals Commonly Used in Furnace Brazing (AWS A5.8)

AWS classification	Minimum copper, %	Brazing temperature, F
BCu-1	99.90	2000-2100
BCu-1a	99.0	2000-2100
BCu-2	86.5	2000-2100

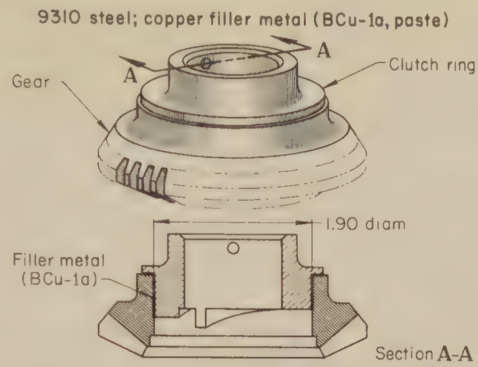


Fig. 6. Gear and clutch-ring assembly that was copper brazed in a hydrogen atmosphere, and later carburized and hardened (Example 545)

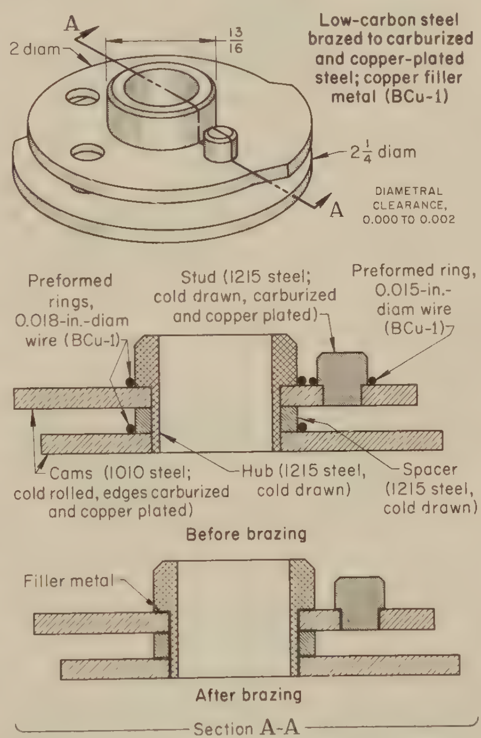


Fig. 7. Cam assembly that was selectively plated for protection of carburized surfaces during brazing (Example 546)

Brazing Carburized Components. A distinct advantage of furnace brazing with copper filler metal is that it permits carburizing before brazing, as well as after brazing. This means that only those components that require hardening need to be carburized. This is advantageous in some applications, such as the one described in the following example, which also gives procedures for satisfactory results.

Example 546. Copper Brazing of an Assembly Containing Carburized Components (Fig. 7)

Three of the five components of the cam assembly shown in Fig. 7 were carburized prior to assembling for copper brazing. The two 1010 steel cams were selectively carburized to produce a 0.020-in. case along the peripheral working surfaces, and the 1215 steel stud was carburized on all surfaces except the tenon portion to the same case depth. Surface carbon content of the case was about 1.1% after carburizing. This initially high surface carbon content compensated for subsequent diffusion during brazing and reheating for hardening. Surface carbon content after austenitizing in a neutral salt and oil quenching was not reported, but was satisfactory for the intended service. Resulting hardness was at least Rockwell 30N 79.

After carburizing, the cams and stud were thoroughly degreased and flash copper plated with a 0.0002-in.-thick coating. The spacer and hub, of 1215 steel, were also degreased, the five components were assembled for brazing, and copper filler metal in the form of preformed wire rings was preplaced as shown in Fig. 7. Diametral clearance ranged from 0.000 to 0.002 in. The assemblies were brazed at 2070 F in a 100-kw electrically heated mesh-belt conveyor furnace (12-in.-wide belt) under a lean endothermic atmosphere. The carbon potential of the atmosphere was maintained between 0.3 and 0.4% C. Brazing time was 11 min per piece and production rate was 1000 assemblies per hour.

Originally, the copper plating had been applied only to the components that had not been carburized (the hub and spacer), in order to protect them from acquiring a hard, difficult-to-machine surface during brazing in an atmosphere of high carbon potential, which was required to keep the carburized components from decarburizing. Copper plate approximately 0.0005 in. thick was needed to protect the surfaces, and it ran during brazing, forming puddles that were difficult to remove. Therefore, it was decided to use an atmosphere that was compatible with the bare noncarburized components, and to copper plate only the carburized components. With the atmosphere of lower carbon potential, a 0.0002-in.-thick copper plate was sufficient to prevent decarburizing of the components to be hardened. The desired results were obtained: use of the thinner copper plate virtually eliminated puddling of the copper, and the atmosphere with the lower carbon potential effectively eliminated sooting in the furnace and in the generator.

Cost of Brazing With Copper vs Silver Alloy Filler Metal. Copper filler metals have the advantage of low cost, especially when compared to filler metals containing silver. Depending on the silver content, the cost (in 1971) of silver alloy filler metal in wire form ranges from 10 to 20 times the cost of an equal volume of copper filler metal, and thus is a significant portion of the total cost of silver brazing. The table that follows shows some typical 1971 costs for butt-end preformed rings of BAg-1, which has a nominal silver

Table 4. Results of a Cost Study To Determine Saving or Loss by Use of Cu-Zn-Ag Instead of Copper Brazing Filler Metal To Increase Life of Mesh Belts by Brazing at Lower Temperature (Example 547)

Item	Filler metal: Copper	Filler metal: Cu-Zn-Ag alloy(a)	Cost saving (+) or loss (—)
Filler-metal consumption per year, lb	1000	1000	...
Cost per pound of filler metal(b)	$ 0.52	$ 5.00	...
Filler-metal cost per year	$ 520	$5000	—$4480
Mesh-belt cost	$3000	$3000	...
Belt life, months(c)	9	18	...
Belt cost per year	$4000	$2000	+$2000
Net loss by use of Cu-Zn-Ag filler metal			—$2480

(a) 53% Cu, 38% Zn, 9% Ag. (b) Using 0.018-in.-diam wire, purchased in 500-lb lots. (c) At brazing temperatures of 2050 F for copper and 1850 F for Cu-Zn-Ag brazing filler metal.

content of 45% and is one of the commonly used silver alloy filler metals:

Ring ID, in.	Cost per butt-end ring formed from wire diameter of: 0.032 in.	0.040 in.	0.062 in.
0.500	1.1¢	1.6¢	3.5¢
0.750	1.5	2.3	5.0
1.000	1.9	2.9	6.5

Costs are based on prices per troy ounce of $1.40 for the 0.032-in.-diam wire, $1.32 for the 0.040-in.-diam wire, and $1.22 for the 0.062-in.-diam wire, plus 0.2¢ per ring for forming and cutting, in lots of 10,000 rings.

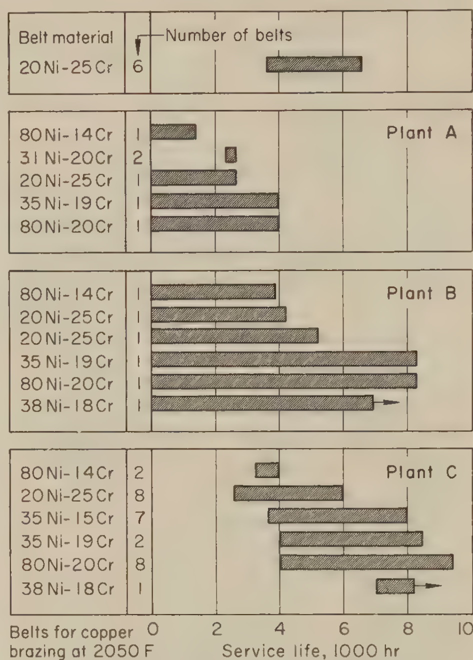
An additional cost for using silver alloy filler metal in furnace brazing is the cost of the flux. For example, the cost of the flux commonly used in brazing with BAg-1 filler metal is about $1.50 per pound. If one pound of flux is used in making 300 joints, the cost of flux per joint is about 0.5¢. However, in many operations, to reduce labor costs, two to three times the minimum amount of flux is applied, at two to three times the material cost. To this must be added the labor cost for applying the flux and for washing the assembly after brazing to remove the flux, and the cost of disposing of the flux-contaminated wash water.

Although furnace brazing using copper filler metal is likely to shorten the life of furnace components and to increase maintenance costs, because of the higher brazing temperatures, the higher cost for silver alloy filler metals, and the cost of flux attack on furnace components (see also Examples 548 and 564), make it the more costly process, as shown in the following example.

Example 547. Cost Study of Furnace Brazing Using Copper and Silver Alloy Filler Metal (Table 4)

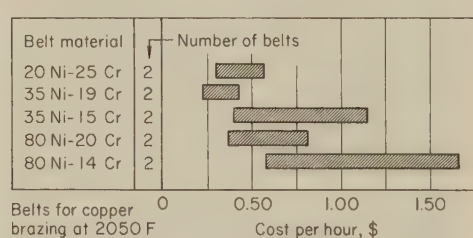
A major maintenance cost of the copper brazing operations at one plant was the replacement of the 12-in.-wide heat-resisting alloy mesh belts used in the five production furnaces. As part of a cost-reduction program, a study was made to determine the possibility of reducing this cost. On the basis of published data that indicated an approximate 50% increase in belt life for each 100 F reduction in operating temperature below 2050 F, the potential benefits of substituting a lower-melting filler metal for copper were investigated.

Laboratory tests with production assemblies indicated that one of the less expensive silver-containing alloys (53% Cu, 38% Zn and 9% Ag, with a melting, or liquidus, temperature of approximately 1400 F) had satisfactory joint-filling properties. However, when this alloy was tried, normal production volume could not be maintained unless the furnace heating chambers were operating at 1850 F, even though a lower temperature would have been adequate for melting and flow of the filler metal. In addition, tests of brazed joints showed an 18% reduction in torque strength, as compared to copper brazed joints, restricting the use of the silver alloy filler metal to parts with relatively low stress levels.



The six belts in the top graph had B 43-11-10 fabricated weave. The belts of plant A had RR 18-17-10 fabricated weave, and those of plant B, RR 23-22-12 fabricated weave. Bars with arrows indicate belts that were still in service at the end of the survey period.

Fig. 8. Service life of woven belts in copper brazing furnaces operating at 2050 F



Mesh belts were of reinforced RR 18-17-10 weave. High cost of 80Ni-14Cr belts was caused by early mechanical failure that resulted from parts sticking to the belts.

Fig. 9. Comparison of costs per operating hour for mesh (woven) belts of five different materials, used in copper brazing furnaces operating at 2050 F

Despite these limitations, the 200 F reduction in brazing temperature suggested a 100% increase in belt life, and preliminary cost estimates were prepared to weigh this potential saving in maintenance cost against the higher cost of the filler metal. The estimates, shown in Table 4, indicated a cost increase of approximately $2500 at the production rates required, not including additional costs of flux, flux application, flux removal, and flux attack on furnace components. As a result, no further consideration was given to using silver alloy filler metal for brazing applications in this plant.

Mesh belts are used in furnaces of various capacities and for loads of various sizes. Figure 8 shows service life for rod-reinforced mesh belts made from several different alloys and used in copper brazing furnaces at 2050 F.

Load-density limits for mesh belts are established mainly by operating temperature, length from the loading position to the discharge end of the heating chamber, belt alloy, cross-sectional area of the belt, the brazing atmosphere used, and an estimate of acceptable life. It is essential that the mesh does not become crushed, either from excessive loading or from parts dropping into the mesh. For an operating temperature of 1450 to 1650 F, a load range of 16 to 140 lb per square foot is usually permissible, but the allowable loading decreases to about 4 to 30 lb per square foot when the temperature is increased to 2050 F.

The performance of certain alloys used for mesh belts is often difficult to explain. For example, in Fig. 8, belts made of 35Ni-19Cr and of 80Ni-20Cr gave the same life in plants A and B. These service data show that use of a high-alloy, high-cost material may not result in lowest hourly operating cost.

In addition to the tensile loading that a mesh belt receives, several other factors influence its life in a furnace.

1. Composition of the oxide coating on the surface affects the amount of friction at the loop connections.
2. Friction at rubbing joints has a significant effect on the degree of pressure welding, and may influence life.
3. Stretching during service changes the contour of the loops, and increases the stiffness of the belt, as does camber or bowing of the cross-rods. A reduction in flexibility, such as is generally encountered when the alloy wire becomes old and brittle, can hasten failure during the return trip of the belt over drive rolls, even though this repeated stress takes place at room temperature.
4. Use of fluxes will reduce belt life, because fluxes spill on the belt and promote deterioration.
5. The contour of the loops and the method of joining at the edges of the belt are equally important. Certain patterns or weaves will perform better on a specific furnace and will yield longer belt life.

Figure 9 also shows that an alloy of lower initial cost may also be less expensive when judged by cost per service hour; two of the lower-alloy materials were superior to the 80% nickel alloys. From a practical standpoint, data on cost per service hour may be incomplete. Other factors should be considered, notably: (*a*) labor cost of repairs, (*b*) loss of productivity during downtime, and (*c*) the possibility of damage to other components if the belt fails (most belts that have been in use for a reasonable period of time are replaced before they break).

Elimination of Flux. Copper filler metals, when used in conjunction with a suitable protective atmosphere in the brazing of steel, are self-fluxing by virtue of the ability of the atmosphere to reduce surface oxides and thereby to promote the flow of filler metal. Fluxes increase brazing costs and contaminate

and corrode heating elements and other furnace components. The relative importance of flux contamination varies considerably among applications. In applications such as that described in the following example, flux contamination may become a dominant factor in the selection of a filler metal.

Example 548. Change From Silver to Copper Brazing To Avoid Contamination of Furnace by Flux (Fig. 10)

Originally, the cam-and-sleeve assembly shown in Fig. 10 was joined by torch brazing, using a silver alloy filler metal, but distortion caused by uneven heating was excessive. When the process was changed to furnace brazing with silver alloy filler metal (BAg-1) and flux (AWS 3A), distortion was reduced, but the contamination and corrosion of furnace rails and exposed heating elements by the fluorides in the flux and the zinc vapors from the silver alloy were objectionable.

Furnace brazing with copper filler metal in a protective atmosphere containing 30% CO, 16% H_2, rem N_2 eliminated the need for a flux (and thus eliminated flux damage). Because a tighter joint fit was used with copper brazing, dimensional requirements were met more easily.

The cam was made of half-hard 1020 steel, and the sleeve, of 1113 steel. The dimensional requirement for both the hole in the cam and the mating diameter on the sleeve was 0.625 + 0.001, − 0.000 in. After being cleaned, the components were assembled in a fixture that held the sleeve in the proper orientation while it was staked; a preformed ring of 0.020-in.-diam BCu-1 wire was placed over the sleeve (see Fig. 10).

The assemblies were brazed at 2050 F in an electric pusher-type furnace with a heating chamber 12 by 36 in. by 8 in. high. Brazing time was 15 min, and production rate was 60 assemblies per hour.

Selection of Filler-Metal Form. Copper filler metal is available in several forms, including wire, strip, special preforms, powder, and a variety of pastes. Occasionally, copper that is to serve as filler metal is deposited on the base metal by electroplating. Selection of the preferred form of filler metal is usually based on joint design, ease of placement in assembly, ability to retain a fixed location during transit through the furnace, and production quantities required. The next three examples discuss the reasons for selecting two forms of filler metal — paste and electroplating — on the basis of the application requirements.

Example 549. Use of a Paste Form of Copper Filler Metal Because of Low Production Volume (Fig. 11)

In the business-machine assembly shown in Fig. 11, the 1215 steel block was projection welded to the 1010 steel arm and then the joint area surrounding the projection weld nugget was furnace copper brazed to provide the strength required in service. In selecting the form of copper filler metal, several factors had to be considered. Production volume was relatively low, and therefore the cost of preforming special copper wires to the desired configuration could not be justified. Placing a piece of wire at the joint would have been unsatisfactory because the wire could be moved out of position by vibration during transit through the furnace. Hand crimping the wire would have prevented displacement, but crimping would have been time consuming and difficult. Mechanical precrimping could not be justified on the basis of production quantity. Under the circumstances, and because fillets in the joint area were not objectionable, filler metal in

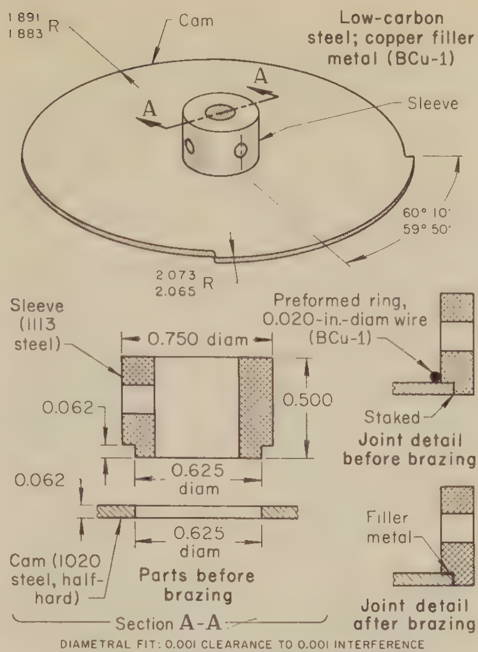


Fig. 10. Cam-and-sleeve assembly that was furnace brazed using copper filler metal, to minimize warpage and eliminate use of flux (Example 548)

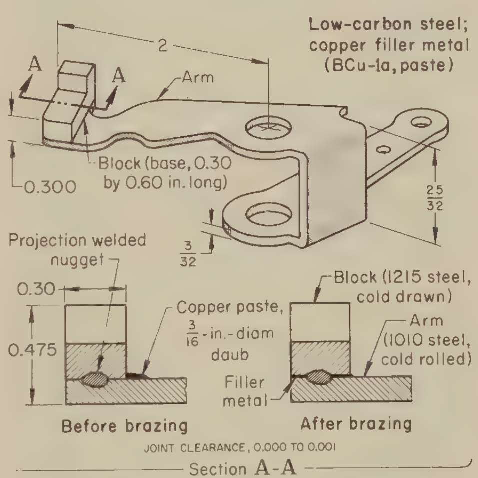


Fig. 11. Business-machine assembly to which copper filler metal was applied as a paste (Example 549)

the form of a copper paste proved most economical and easiest to apply. The paste was applied to one side of the joint in the form of a daub about 3/16 in. in diameter (see Fig. 11).

The assemblies were brazed at 2070 F in a 100-kw electrically heated mesh-belt conveyor furnace (12-in.-wide belt), in an endothermic atmosphere. Time in the heating chamber was 9 min, and the production rate was 900 assemblies per hour.

Examples 550 and 551. Use of Copper Plating as a Filler Metal To Control the Volume of Copper in Brazed Joints

Example 550 — Plate-and-Stud Assembly (Fig. 12). The small size of the two studs and adjacent joint areas in the plate-and-stud assembly shown in Fig. 12 required close control of the amount of copper in the brazed joint. Copper paste applicators could not deliver the required volume with enough accuracy. Manual placement of wire rings was not feasible because the small diameters of the wire and ring would make placement slow and tedious. Automatic ring placement was feasible, but could not be justified because of low production rate. The stud tenons could have been dipped in copper paste before assembly by press fitting, but dipping would have been slow and messy unless mechanized — an expense that was not justifiable.

Copper plating the studs in a barrel proved to be feasible and economical. Plating time and operating conditions had to be accurately controlled to ensure an optimum thickness of copper — enough to fill the joint without developing an excessive fillet at the joint or copper puddles in critical areas. Plating thickness was controlled by a drop test to 0.00012 to 0.00023 in. Diametral clearance between stud and plate was held to 0.0000 to 0.0015 in.

The degreased components (1010 steel plate and 1215 steel studs) were assembled and then brazed in a 100-kw electric mesh-belt conveyor furnace (12-in.-wide belt), in an endothermic atmosphere. The brazing time was 8 min at 2070 F. Production rate was 2200 assemblies per hour.

Example 551 — Hub-and-Lever Assembly (Fig. 13). The small assembly shown in Fig. 13, consisting of a 12L14 steel hub and a 1020 steel lever, was furnace brazed using 0.0003-in.-thick copper plate on the hub as the filler metal. Plated filler metal was selected because copper paste could not be

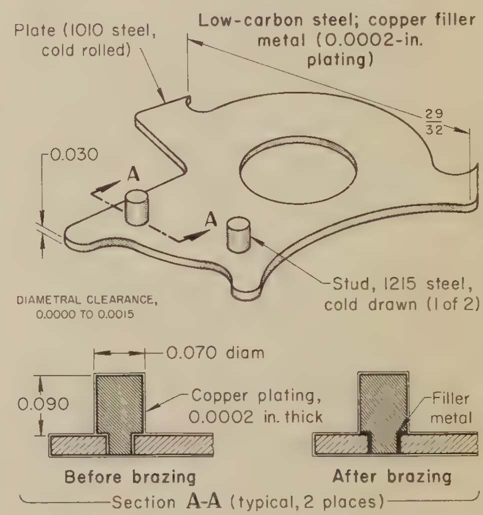


Fig. 12. Plate-and-stud assembly with small brazed joints to which filler metal was applied by plating (Example 550)

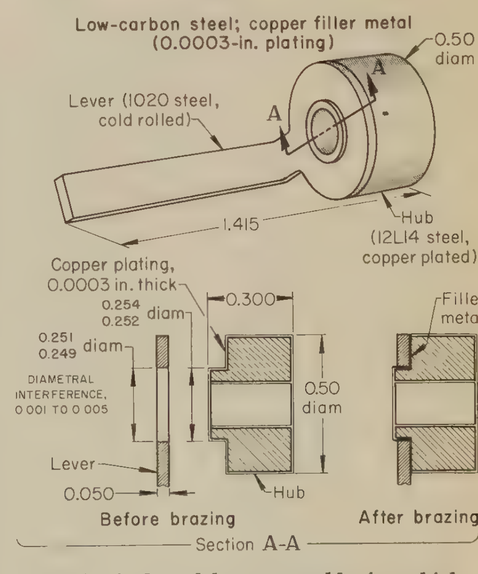


Fig. 13. Hub-and-lever assembly for which close control of volume of brazing filler metal was provided by plating (Example 551)

applied with equivalent uniformity of volume and because a preplaced copper wire ring, although otherwise satisfactory, might have fallen from the joint location during transit through the furnace.

The plated hub and the vapor degreased lever were assembled with a diametral interference of 0.001 to 0.005 in. and were brazed in a protective atmosphere containing 30% CO, 16% H_2, rem N_2 in a pusher-type furnace at 2050 F. Brazing time was 10 min, and the production rate was 400 assemblies per hour.

Cleaning and Surface Preparation for Brazing

Cleaning is almost always advisable before brazing because the presence of oil, grease, pigmented drawing lubricants, excessive amounts of oxide, and other surface contaminants in or near the brazed joint will have a deleterious effect on the soundness and strength of the joint. Some contaminants will interfere with the wetting action, so that normal flow of molten filler metal in the joint will be prevented.

Both chemical and mechanical cleaning methods are used to clean steel components and assemblies for brazing, but chemical methods are the more widely used. Chemical methods include akaline cleaning, solvent cleaning, vapor degreasing, and sometimes acid pickling. The mechanical methods most commonly used are dry and wet abrasive blast cleaning. Other cleaning methods, if they prove satisfactory, are employed largely because the necessary equipment is available. If warranted, machining or grinding may be used to obtain the necessary joint cleanness, and to ensure satisfactory wetting.

Chemical Cleaning Methods. Alkaline cleaning, including soak, spray and barrel cleaning, is widely used for removing oily, semisolid or solid soils from steel components before furnace brazing. It is generally satisfactory for removing most cutting and grinding fluids, grinding and polishing abrasives, and some pigmented drawing compounds. The solutions, methods, equipment requirements, advantages and limitations, as well as costs, are described in the article on pages 317 to 325 in Volume 2 of this Handbook.

Solvent cleaning is capable of removing oil, grease, loose metal chips, and other contaminants from steel components. Parts are immersed and soaked in a common organic solvent. Spray methods can also be employed. The solvents, process variables, equipment, and limitations of solvent cleaning are described in the article on Solvent Cleaning, pages 330 to 333 in Volume 2 of this Handbook.

Vapor degreasing, a cleaning process used in a number of the examples in this article, employs the hot vapors from a boiling chlorinated hydrocarbon solvent to remove surface contaminants such as oils, greases and waxes. To supplement the vapor, some degreasing units are equipped with facilities for immersing the work in the hot solvent or for spraying with clean solvent. Solvents, procedures, equipment, costs, and other aspects of the cleaning process are described in the article on Vapor Degreasing, pages 334 to 340 in Volume 2 of this Handbook.

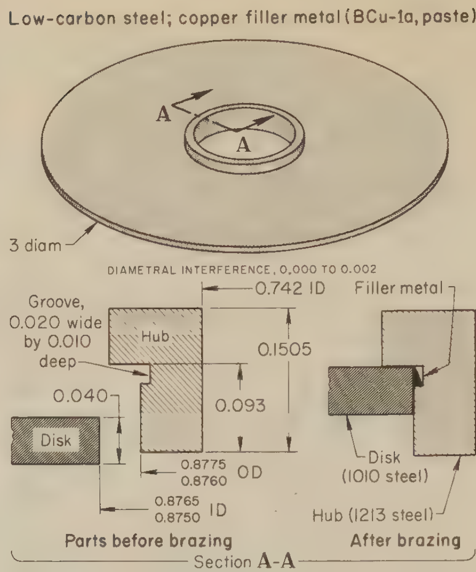


Fig. 14. Brazed type-wheel assembly for which cleaning method was changed from tumbling in abrasive oxides to belt sanding to improve flow of filler metal (Example 552)

Mechanical Cleaning Methods. As previously noted, mechanical methods are less widely used than chemical methods in cleaning for brazing. However, they are usually preferred for removing heavy scale and may be indispensable in removing the more tenacious lubricants, such as a pigmented drawing compound. Mechanical methods are also useful in surface preparation that involves abrading or roughening, which may be required on a very smooth surface to promote wetting and filler-metal flow.

In dry grit blasting, the grits used on carbon and low-alloy steels consist of angular metallic particles of chilled cast iron or of hardened cast steel. Wet blasting employs many different kinds and sizes of abrasives suspended in a liquid carrier. Certain ingredients in the liquid carrier, such as rust inhibitors and the minerals in the water, may adversely affect the wetting action in brazing, and could require an additional cleaning process to remove all traces of liquid carrier from the work. The abrasives, equipment and procedures used in both dry and wet blasting are described in the article on Abrasive Blast Cleaning, pages 364 to 370 in Volume 2 of this Handbook.

Special processing problems, or a high rate of production, may require the use of other mechanical cleaning methods, such as tumbling, belt sanding, grinding, wire brushing, and machining. In the next example, belt sanding proved to be the optimum cleaning method for the application.

Example 552. Substitution of Belt Sanding for Tumbling as a Cleaning Method for Furnace Brazing (Fig. 14)

The 1010 steel disk and 1213 steel hub that comprised a type-wheel assembly (see Fig. 14) were cleaned by belt sanding prior to assembly and brazing. Originally, the components had been tumbled in abrasive oxides to deburr and clean them in the same operation, but tumbling resulted in surface contamination that caused the molten copper filler metal to gather in droplets rather than to flow into the joint. With belt sanding, there was no surface contamination and the filler metal flowed properly.

After belt sanding, the components, which were machined to provide tenon-hole diametral interference of 0.000 to 0.002 in., were assembled by staking. Copper filler metal was applied in paste form. Assemblies were brazed in a mesh-belt conveyor furnace (12-in.-wide belt) at 2050 F, in an endothermic atmosphere. Total heating and cooling time was 30 min. Brazed assemblies were subsequently carburized. The brazing production rate was 125 disk-and-hub assemblies per hour; 250,000 assemblies were produced annually.

The joint design used for the assembly discussed in the foregoing example is not considered good (specifically, the 0.020-by-0.010-in. groove). The groove was initially intended to contain a filler metal wire and was not redesigned when a change was made to paste. However, an acceptable joint was made by the procedures described.

Stop-offs

Under ideal conditions, the filler metal flows by capillary action and, in so doing, completely penetrates the joint. In practice, flow may not stop when the joint is filled, and filler metal may flow onto areas where it is not wanted. For example:

1. In brazing a threaded stud into a part, the filler metal is likely to follow the threads and render them out-of-tolerance.
2. Support points on fixtures used in furnace brazing may become wetted by the filler metal, producing an unwanted braze and perhaps resulting in loss of the fixture and assembly, because it may be impossible to separate them without damage.
3. Some parts, such as turbine and compressor brazements, are designed to close tolerances and excess filler metal may be dimensionally objectionable.
4. Tubular assemblies, particularly small capillary tubes (1/16-in. ID or less), can easily become partly or completely blocked with filler metal.
5. Excess filler metal may be unacceptable because of appearance.
6. In production brazing, where it may be necessary to use more filler metal than called for to allow for variations in fit-up between parts, some joints will have excess filler metal, which will flow away from the joint area.

Stop-off Materials. For brazing carbon and low-alloy steels in the more commonly used atmospheres, such as exothermic-base, milk of magnesia painted on the appropriate areas is an effective stop-off. Also, painting fixtures with a water solution of chromic acid and then heating them to the brazing temperature renders them resistant to wetting by the filler metal, because a thin layer of chromium oxide forms.

For brazing in a hydrogen atmosphere or in vacuum, the two proprietary materials used are composed of oxides of aluminum, titanium, magnesium, and sometimes of other elements. One is fast drying, and behaves much like a commercial lacquer, the thinners being commercial lacquer thinners such as acetone. The second is a nonwicking type, composed of oxides in a gelled vehicle, that does not settle out on standing; this type dries slowly.

Methods of Applying Stop-off. For large areas, the use of a paintbrush or

a paint roller is a satisfactory method of applying stop-off. This method is used to protect touch points of metal fixtures. Often, it is advisable to repaint the fixture prior to each use, because some stop-off may crack off during each heating cycle.

The use of an artist's brush is ideal for precision application of fine areas of stop-off, although the operation is time consuming and requires considerable skill.

Use of a medical syringe makes it possible to obtain extremely fine detail in stop-off. Needles of 0.010-in. ID are often used. With a small needle, a drop of stop-off can be applied at a precise point. Hypodermic syringes are not suitable for use with fast-drying stop-offs, because the needles soon become clogged.

With the fast-drying type of stop-off, there is always danger that some of it will inadvertently run into the joint area. If this happens, the assembly must be taken apart and all stop-off must be removed.

A nonwicking stop-off can be applied by conventional equipment designed for application of liquid plastics, paste brazing alloys, and other organic compounds. It will remain stable over long periods of time, and will not clog the valves and tubing in the system.

Assembly for Brazing

The component parts of an assembly to be furnace brazed must be assembled in an essentially fixed position before entering the furnace, and they must be capable of maintaining this position throughout brazing and cooling. The filler metal, a part of the assembly, must be preplaced in the proper location and in the most convenient form, and it must maintain this location.

Self-jigging is the method of assembly in which the component parts incorporate design features that will ensure that the components, when assembled, will remain in proper relationship throughout the brazing cycle without the aid of auxiliary fixtures. This is the preferred method of assembly, as it eliminates the initial and replacement cost of auxiliary fixtures and the cost of heating them during brazing, and it usually is a more sure method of holding the components. Self-jigging can be accomplished by several methods, including gravity locating, interference or press fitting, knurling, staking, expanding, spinning, swaging, crimping, thread joining, riveting, folding, peening, and tack welding, as shown in Fig. 15. In addition to the self-jigging techniques described in this section, numerous applications of self-jigging are given in the examples in this article.

Gravity Locating. Perhaps the simplest method of assembling two components is to rest one on top of the other with the brazing filler metal either wrapped around one component near the joint (Fig. 15a) or placed between components (Fig. 15b). The principal disadvantage of gravity locating may be the lack of a dependable means of orienting the components or keeping them from moving in relation to one another. Nevertheless, some production components are assembled in this manner, especially those in which the upper component is relatively heavy.

Interference or press fitting, which requires expansion or contraction of mating component surfaces, provides a very tight fit — sometimes called a "tight press fit". Interference fitting is illustrated in Fig. 15(c) and (d). In Fig. 15(c), the cup has an inside diameter that is smaller than the mating projection of the underlying plate. The extent of interference seldom exceeds about 0.001 in. per inch of diameter, up to about 3-in. diameters. Nevertheless, most interference fits require considerable force to achieve assembly, a force generally provided by an arbor press or similar tool. Thus, an interference fit is a press fit.

Lighter interference fits, such as that shown in Fig. 15(d), may provide zero clearance or a very slight gap between the mating surfaces of components. These, too, require some external force, such as that provided by an arbor press, to achieve assembly. Fits with zero clearance are referred to as "size-to-size" fits. Some method is used to prevent slippage when the components are heated in the furnace, particularly if the joint has a vertical axis. As shown in Fig. 15(d), a shoulder on one of the components can be used to ensure stability.

Knurling. In high-production manufacturing, there will be considerable variation in joint clearance among the assemblies being brazed. Typical brazed assemblies in which a round male member is fitted to a female member are subject to either of two conditions: (*a*) the male part is off-center, thus allowing all of the diametral clearance on one side, or (*b*) the male member is out-of-round, so that all of the clearance will be on two opposite sides with no clearance (or even interference) on the other two sides.

Knurling the end of the male member (Fig. 15e) is sometimes a way of correcting the conditions described above and obtaining uniformity among brazed joints. Often, knurling can be done during machining of the part, thus adding very little to the cost. If knurling must be done in a secondary operation, the extra cost often can be balanced against the cost of the rejects that would be encountered if knurling were not done.

When the male member is tubular, prick punching may be substituted for knurling. Usually two rows of prick punch marks near the end of the male member are sufficient. Prick punching is easily done, but since it involves a secondary operation, the cost must be justified.

Staking. Figure 15(f) shows how staking will effectively lock two components in position. Burrs are turned up on the shaft by driving a punch into it. This method, of which there are a number of modifications, is commonly used to retain the orientation of such assemblies as cams, levers and gears on shafts or on common hubs. It is sometimes a substitute for tack welding, knurling or interference fitting.

Expanding. This method is commonly used in assemblies of tubes to tube sheets. The tubular component is pressed into a header sheet and expanded in the hole to lock the assembly, as shown in Fig. 15(g). Rings of brazing filler metal can be placed over the tube before or after the expanding operation. To avoid obtaining a mere line contact in expanding, a leader can be placed on the expanding tool to project into the tube and support the tube wall while the end of the tube is being flared.

Spinning. When the diameter of a hole in an assembly may not be altered during assembly, as when a hub is fastened to a lever, the assembly can be locked together, as shown in Fig. 15(h), by spinning in a

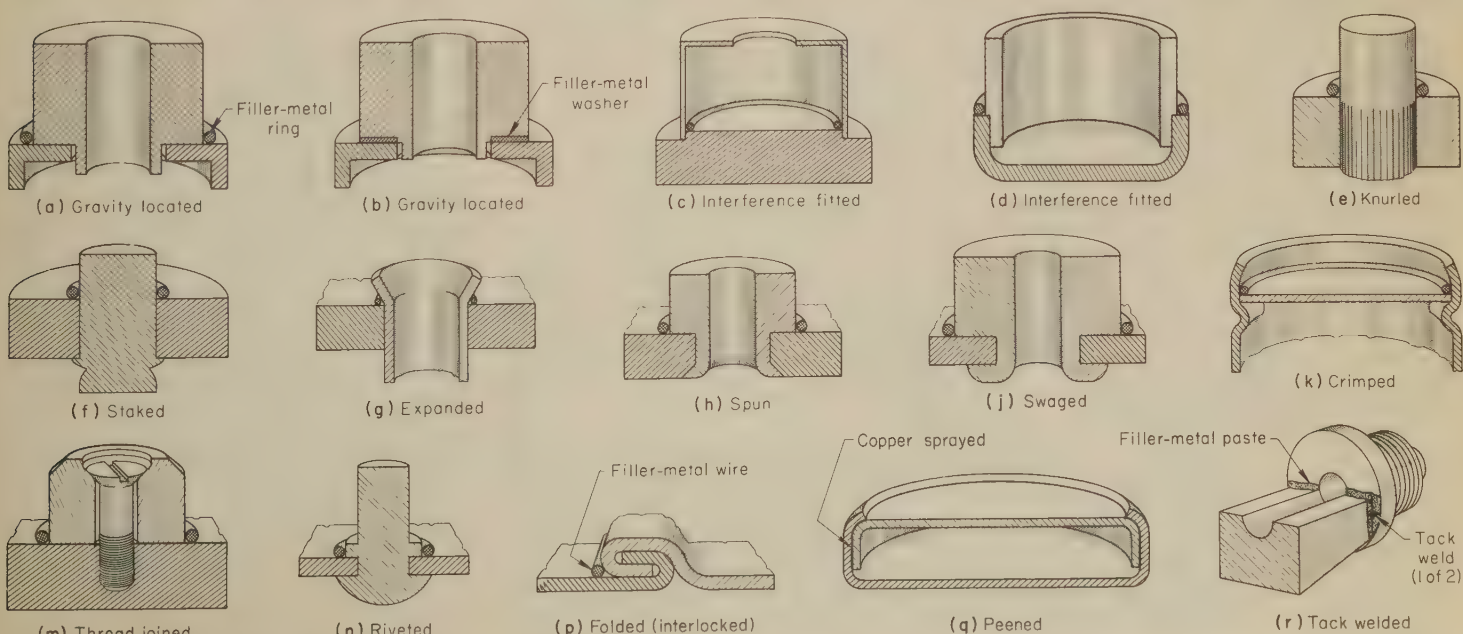


Fig. 15. Assemblies illustrating the use of several methods of self-jigging, to hold components together for furnace brazing

riveting machine. The same result can be obtained by flaring the tenon in a press. Tolerances for the punched hole and tenon must be held closely, to ensure the close joint clearances required for brazing. The punched hole must be chamfered, as shown in Fig. 15(h), to allow room for the spun or pressed end of the tenon. The spinning method of assembly is used for parts for various types of business machines, many of which were formerly assembled by cross drilling and pinning the hubs.

Swaging. An inexpensive and effective method of assembling a spud in a hole in a hollow body is to swage it in place, as shown in Fig. 15(j). This method is acceptable when it is not necessary to maintain accuracy of the diameter of the hole in the hub and when the projection on the flange can be tolerated. The principal advantage of swaging is that close tolerances do not have to be held on the tenon or the punched hole because the swaging operation forces the components into intimate contact. In addition to other applications, swaging has been used to assemble a valve body in a float chamber for refrigerators. The resulting bond after furnace copper brazing is strong, tight, leakproof, and capable of withstanding high pressure.

Crimping. Figure 15(k) shows the assembly of a disk, shell, and copper filler-metal ring in which the disk and ring are held in place by crimping the end of the shell. Also shown is an inexpensive method of forming "stoppers" against which the disk is located; these stoppers consist of three or four indentations around the shell.

In general, it is preferable to set an assembly of this type on end in the furnace so that the filler metal will flow downward through the joints. However, if the tubular component is long, the assembly must be laid on its side to clear through the furnace, and so an oversize ring of hard copper wire filler metal that can be sprung in place close to the joint is used. If the diameter of the tube is 2 in. or more, the filler-metal wire and adjoining steel surfaces should be coated with copper powder paste, which will harden and prevent the wire from sagging away from the joint at the top as the assembly is heated. The paste also provides an auxiliary supply of filler metal.

Thread joining has been used for assembling components of replacement punch holders for die sets used in punch presses.

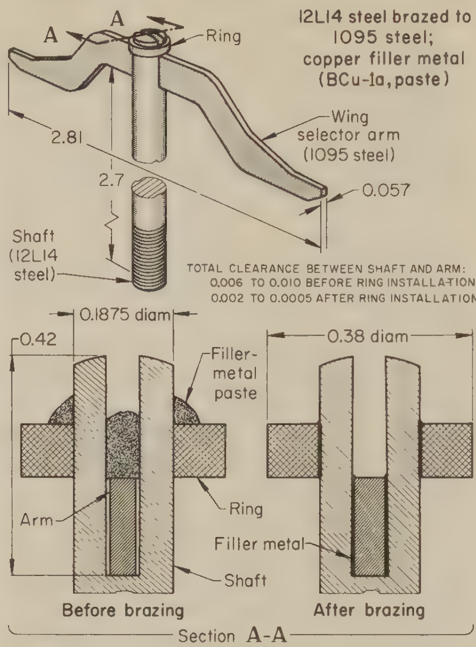


Fig. 16. Use of a press-fit ring to obtain self-jigging in a shaft and selector-arm assembly (Example 553)

As shown in Fig. 15(m), the shank is held in place on the punch-holder plate by a screw. Because drilling and tapping are required, this method of assembly is generally limited to small production quantities.

Riveting, illustrated in Fig. 15(n), is a modification of the spinning and swaging methods that uses a rivet as part of the assembly. It is widely used to assemble the vanes to the outer disks of fan wheels before furnace copper brazing. The combination of riveting and copper brazing markedly extends the service life of the assembly.

Folding or Interlocking. Several methods and designs of folding or interlocking can be used to secure joints, such as that shown in Fig. 15(p). These methods are widely used in the manufacture of brazed tubing or tubular assemblies. Copper filler metal is supplied either in the form of copper plating or by wedging a copper wire at the base of the joint. Capillary action will draw the filler metal to all areas of the joint.

Peening. Assembly of two hollow shells by the peening method is shown in Fig. 15(q). The stamped components are pressed together, and the outer shell is peened with an air hammer along the periphery. To apply filler metal to an assembly of this type, copper can be sprayed on the joint interfaces before assembly, using an oxy-acetylene spray gun.

Tack Welding. Prior to copper brazing, the tip and shank of the electrode holder for an atomic-hydrogen welding torch were assembled by tack welding, as shown in Fig. 15(r). Filler metal consisted of a small amount of copper powder paste daubed around the joint. Any oxide formed during tack welding was reduced by the protective atmosphere during furnace brazing.

The tack welding method of assembly usually requires careful investigation to determine the most strategic point or points for placing the weld. For economy, the number of tack welds per assembly should be held to a minimum.

Examples of Practice. Methods of assembly that involve pinning, wedging or winding are also feasible in some applications, and there are a great many modifications and combinations of conventional methods. In the example that follows, the interference-fitting method of assembly was modified by the use of an auxiliary ring to clamp the major components in position, rather than interference fitting one to the other.

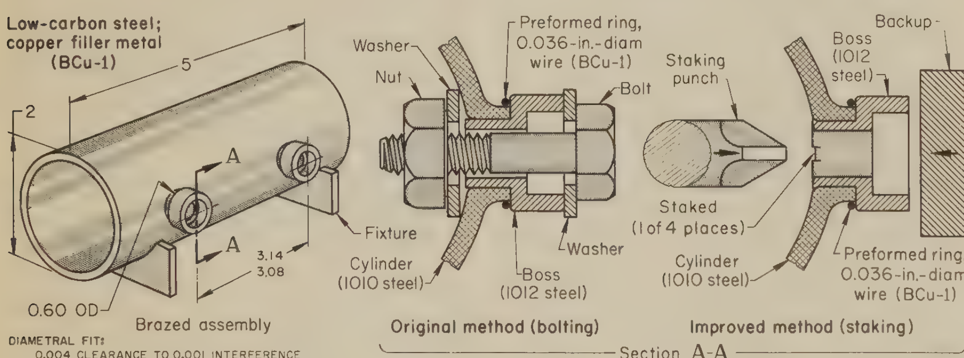


Fig. 17. Change from bolting to staking as the method of holding fuel bosses to a fuel cylinder prior to furnace brazing. Improved method reduced manufacturing cost by 30% and increased production rate by 150%, compared with original method (Example 554)

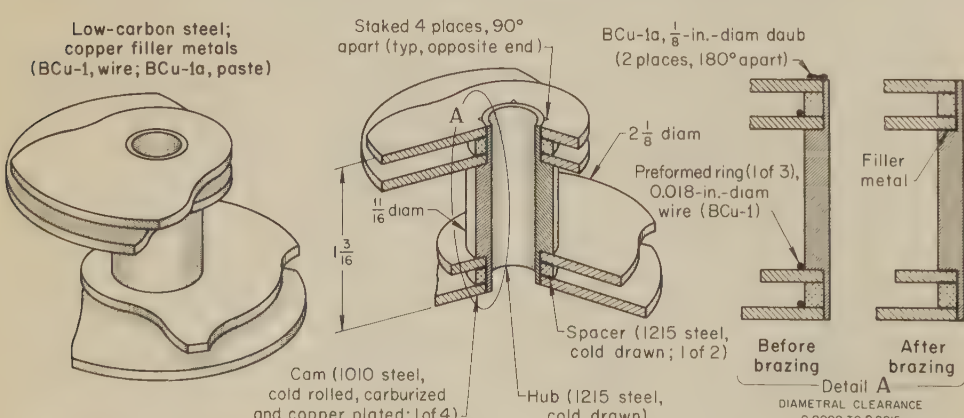


Fig. 18. Multiple-cam assembly for which the method of self-jigging for brazing was changed from riveting to square staking to eliminate radial stress that caused warpage (Example 555)

Example 553. Use of a Press-Fit Ring To Obtain Self-Jigging (Fig. 16)

The 12L14 steel shaft and 1095 steel selector arm shown in Fig. 16 presented a problem in assembly and in the application of brazing alloy. The problem was solved by increasing the depth of the slot in the top of the shaft 3/16 in. beyond the initial depth, permitting the selector arm to seat farther into the slot and providing clearance at the top of the shaft for placement of a press-fit ring. Joint clearance was 0.003 to 0.005 in. on each side of the selector arm before application of the ring. Over-all clearance was reduced to 0.0005 to 0.0020 in. after placement of the ring. This arrangement held the selector arm tightly in position. Filler metal was applied in the form of a paste made from BCu-1a powder (99.0% min Cu). The paste was applied above and around the brazed area to permit flow downward into the joint. The ring was brazed in place.

Before brazing, the assemblies were placed in brazing jigs, which consisted of blocks of graphite 12 by 5 by 3 in. thick containing 40 holes drilled to accommodate the shafts of 40 assemblies. The assemblies were brazed in a mesh-belt conveyor furnace, at a belt speed of 6 in. per minute. The brazing temperature was 2050 F, and the protective atmosphere was dissociated

ammonia. After cooling in the cooling chamber under a protective atmosphere, the assemblies were immersed for 1 hr in a chromic acid solution to remove excess copper. With this setup, it was possible to braze 1200 assemblies per hour, although the preparation rate was only 400 assemblies per hour.

After cleaning, assemblies were inspected by metallographic examination on a sampling basis for completeness of penetration, decarburization, and defects such as voids. Absence of decarburization was important because the 1095 steel selector arm was highly susceptible to decarburization.

Because it requires no special tooling, bolting is an inexpensive means for jigging assemblies in some applications, particularly for low production, but because of the manual labor required to apply and remove the bolt, it may be expensive in others. In the following example, the substitution of staking for bolting resulted in a large reduction in cost and production time.

Example 554. Substitution of Staking for Bolting To Reduce Costs of Assembling Components (Fig. 17)

Manufacturing cost was reduced by 30% and production rate was increased from 100 to 250 assemblies per hour when staking replaced bolting as the method of holding 1012 steel fuel bosses in a 1010 steel fuel cylinder prior to copper brazing. Figure 17 illustrates both methods and shows the completed assembly after brazing.

Staking was done in a press, with the offset staking punch entering the fuel boss from inside the cylinder while the boss was held firmly in place by an external nesting tool.

Assemblies were brazed at 2040 F in a mesh-belt conveyor furnace, in an endothermic atmosphere. Brazing time was 11 min; time in the cooling chamber was 29 min. A preformed ring of 0.036-in.-diam copper wire (BCu-1) was used for the filler metal.

Riveting necessarily imposes high stresses on the components being riveted; in many applications, these stresses may have no significant effect on the quality or performance of the assembly. However, in the application described in the following example, the stresses of riveting resulted in excessive warpage during brazing, which led to the adoption of staking.

Example 555. Change From Riveting to Square Staking To Eliminate Warpage During Brazing (Fig. 18)

When the multiple-cam assembly shown in Fig. 18 was assembled by riveting, high radial stresses were set up in joint areas between the hub and the four cams. When these stresses were thermally relieved during the brazing cycle, the resulting warpage altered the radial positioning of the cams beyond specified limits. To eliminate warpage, staking was substituted for riveting as the method of assembly.

The cams were made of cold rolled 1010 steel and were selectively carburized to produce a case 0.020 in. deep on the working edges. They were copper plated (0.0002 in. thick) before brazing to protect the carburized surfaces. The hubs and spacers were made of 1215 steel. All components were vapor degreased before assembly.

Diametral clearance for brazing was 0.0000 to 0.0015 in., and two forms of copper filler metal were used. Preformed rings of 0.018-in.-diam copper wire were placed at joints above three of the cams, and two ⅛-in.-diam daubs of copper powder paste were placed 180° apart at the periphery of the hub, as shown in Fig. 18.

The assemblies were brazed at 2070 F in a 100-kw, mesh-belt conveyor furnace (12-in.-wide belt), in an endothermic atmosphere with a carbon potential of 0.30 to 0.40%. Heating time was 10 min, and production rate was 500 assemblies per hour.

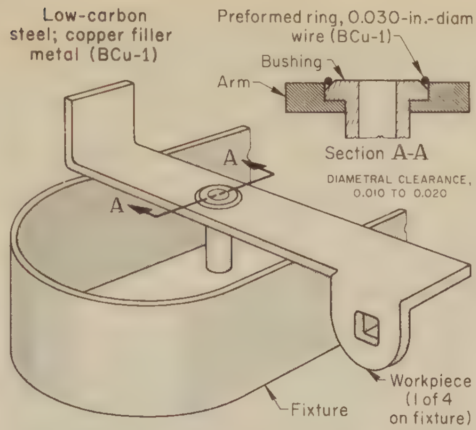


Fig. 19. Arm-and-bushing assembly in position on a simple steel-strap fixture, ready for furnace brazing

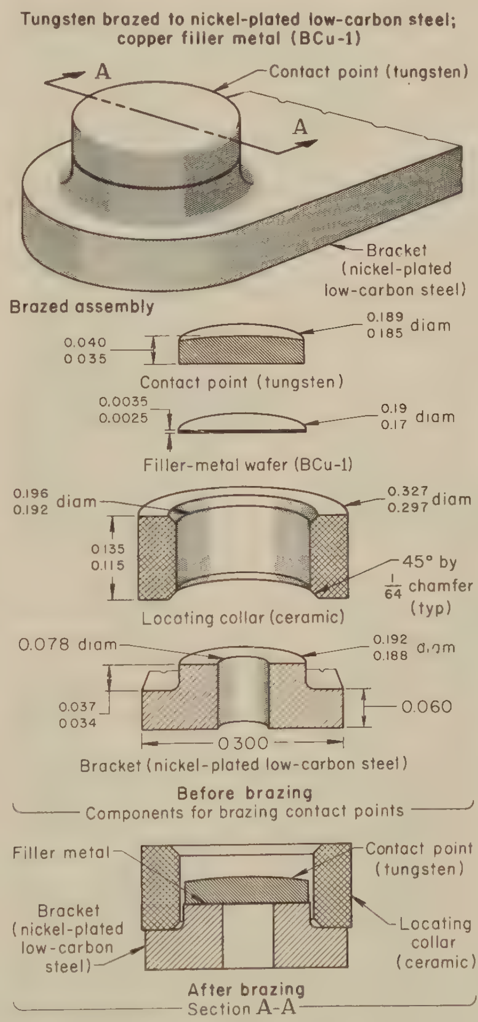


Fig. 20. Distributor-point assembly for which collar used for locating components during brazing was made of ceramic for resistance to wetting by filler metal (Example 556)

Auxiliary Fixtures. In assembling some components for furnace brazing, self-jigging may not be feasible or the assembly may require additional positioning or support that cannot be provided by self-jigging alone, and so the use of auxiliary fixtures is unavoidable. These fixtures can take the form of a simple bracket or wire stand, machined graphite blocks, clamps, or cast supports.

An example of an extremely simple fixture for supporting arm-and-bushing assemblies is shown in Fig. 19. The fixture, a steel strap bent to a U-shape, supported four assemblies in the preferred position for brazing. It provided clearance for the lugs at the end of the arms, and supported the bushing in the vertical position (see Fig. 19) so that the copper filler metal would flow downward into the joint. These assemblies, made of low-carbon steel, were brazed in a conveyor furnace with a 12-in.-wide mesh belt and an exothermic atmosphere.

Low-carbon steel is commonly used for fixtures for short runs; it has the advantage of low cost and the disadvantage of low strength at brazing temperatures. For long production runs, stainless steel and wrought and cast heat-resisting alloys are used.

Fixture design should adhere to the following principles:

1 Sections of fixtures should be as thin as possible, consistent with required rigidity and durability.
2 Fixtures should be designed for minimum contact with the assembly. Point or line contact is preferable to overall surface contact.
3 In general, external fixtures should expand faster, and internal fixtures slower, than the assembly; in applications where tight clamping is required, the reverse is true.
4 To equalize pressure on the assembly from shrinkage during cooling, systems of levers, cams and weights can be used. Wedges and weights often provide good follow-up.

Fixtures are closed or clamped by driving wedges into slots and lugs. The wedges can be easily removed after the assembly is brazed. Spring clamps are seldom used because they undergo relaxation at the brazing temperatures. However, spring clamps made of Inconel, which do not relax as much as those made of carbon steel, are sometimes used. Threaded fasteners should be avoided; if used, they should be made to loose fits, and may be coated with a magnesium hydroxide and alcohol mixture to prevent sticking.

Wetting of Fixtures. Even with a minimum number of contact points between the fixture and the components to be brazed, it is sometimes difficult to prevent the fixture from being wetted by filler metal and sticking or being brazed to the assembly. If the contact surface between fixture and components must be extensive, as in the application described in the following example, selection of a fixture material that resists wetting becomes critical.

Example 556. Selection of Fixture Material for Nonwetting Properties (Fig. 20)

In the assembly shown in Fig. 20 (a distributor-point assembly consisting of a nickel-plated low-carbon steel bracket and a tungsten contact point), a special locating collar was needed for properly positioning a wafer of copper filler metal (BCu-1) and the tungsten contact point with respect to the raised boss on the bracket.

Initially, collars made of steatite (magnesium silicate) were selected, but frequently

these collars were wetted by the copper filler metal and became bonded to the assembly. This necessitated 100% inspection of the finished assemblies and removal of the attached collars. In addition, many collars had to be scrapped after removal.

Several other nonmetallic materials were tried, including a denser steatite, a barium-containing ceramic, a special glass that is resistant to thermal shock, and a lithium-aluminum silicate type of ceramic. Only the special glass and the lithium-aluminum silicate ceramic exhibited satisfactory wetting resistance; the silicate material was finally selected because it was less brittle, could withstand repeated handling, and was less expensive. The change in collar material resulted in a considerable saving in inspection and processing labor and in collar-material costs.

The sequence of operations in assembling and brazing the components was:

1. Seventeen of the contact brackets were placed on a stainless steel furnace-tray fixture.
2. The fixture was placed under a mechanized collar-feeding device, which automatically dropped 17 ceramic collars over the raised bosses on the brackets.
3. The fixture was placed under a feeding device that, by means of vacuum, picked up and deposited 17 filler-metal wafers in position over the bracket bosses.
4. Tungsten contact points were manually set in place within the ceramic collars above the copper wafers.
5. Fixture trays were placed on a 12-in.-wide mesh belt entering a 71-kw electric conveyor furnace at a speed of 8 in. per minute.
6. Assemblies were brazed at 2050 F in an endothermic atmosphere containing 40% hydrogen, 40% nitrogen, and 20% carbon monoxide (dew point, +65 F).
7. After cooling under a protective atmosphere, assemblies were unloaded at the opposite end of the furnace. Heating time was 6 min, and time in the cooling chamber was 30 min.

The furnace was capable of brazing 3400 assemblies per hour, but the number actually brazed depended on the number of operators available for preparing the assemblies. Average production per hour was about 1200 assemblies.

Complex Fixturing. Although simplicity in jigging and fixturing for furnace brazing is highly desirable, complex fixturing is sometimes unavoidable. The following example describes the use of a specially designed fixture for copper brazing of propeller-blade components to aircraft quality standards.

Example 557. Copper Brazing Propeller-Blade Components in a Complex Special Fixture (Fig. 21)

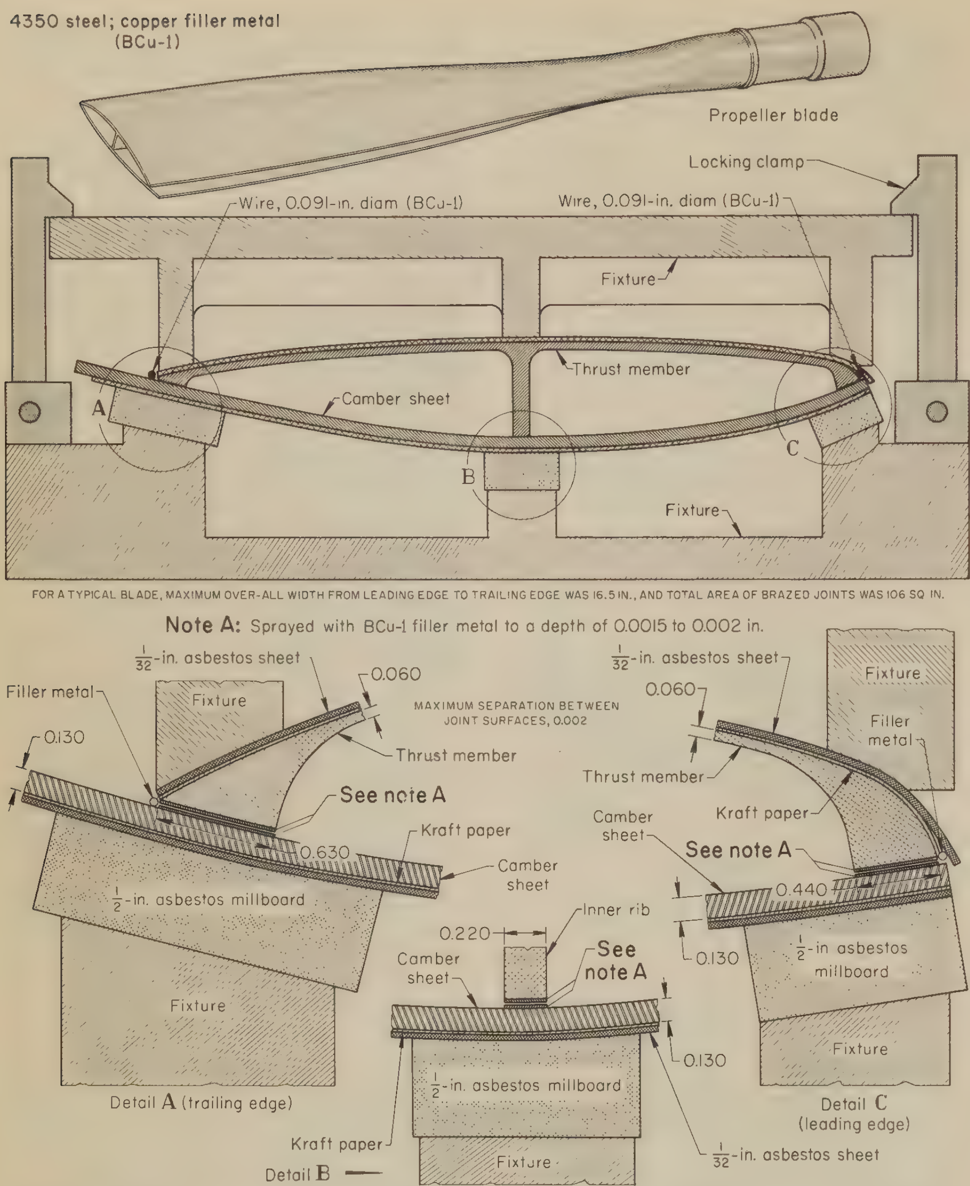


Fig. 21. Propeller blade, and cross section of blade and specially designed fixture for furnace brazing (Example 557)

Two components of a propeller blade — a thrust member and a camber sheet — were successfully brazed to aircraft quality standards, using a complex special fixture that provided accurate contact of the brazed joint surfaces over the variable cross section and contour of the blade length from hub end to tip end. A typical cross section of the blade components in the fixture is shown in Fig. 21. Both the thrust member, which was contour machined from a forging, and the camber sheet, which was cold formed in a die and then die formed and sized at 1000 F, were made of aircraft-quality 4350 steel.

After machining operations were completed, the brazing joint surfaces of the thrust member were hand filed to match the contour of a template. Final checking for fit was done by placing a sheet of carbon paper between the components and clamping them together in the brazing fixture with 29 to 30 tons of force. After the components were removed from the fixture, high spots on joint surfaces, indicated by marks from the carbon paper, were hand filed. By this procedure, separation of joint surfaces was held to a maximum of 0.002 in. Index marks were made on both components to ensure accurate realignment during final assembly.

The joint surfaces were grit blasted, degreased, and dried with an air blast. From then on, the components were handled with clean, dry gloves.

The copper filler metal was deposited by spraying the joint surfaces in the following manner. A template was clamped to the thrust member, and another to the camber sheet. These templates masked off all except the joint area. A predetermined length of precleaned 0.091-in.-diam BCu-1 filler-metal wire was used to spray a copper coating 0.0015 to 0.0020 in. thick on the exposed surfaces.

After spraying, a proprietary high-temperature brazing flux that is active in the range from 1600 to 2000 F was diluted with eight parts of distilled water and sprayed in a thin coat over the joint surfaces of both members. The flux was used to ensure good flow of filler metal in the event of deterioration of the atmosphere in any part of the large brazing furnace.

Before brazing, from one-third to one-half the length of the leading edge of the blade, beginning at the tip, was resistance seam welded, to protect this edge from damage in service caused by impact with another object. If brazing was not to be performed within 8 hr after welding, the blade was placed in a plastic bag to keep it clean.

For brazing, the assembly was placed in the fixture as shown in Fig. 21. Asbestos millboard and sheet distributed the pressure of the fixture (made of 25Ni-20Cr cast heat-resistant alloy) uniformly over the components so that the 19-to-20-ton clamping force that was applied was transmitted evenly to the joints. Kraft paper placed between the asbestos sheet and the assembly facilitated handling and burned to form an ash during the brazing cycle. The ash kept the asbestos from sticking to the blade surfaces. Carefully measured lengths of 0.091-in.-diam BCu-1 copper wire were placed at predetermined intervals along the trailing edge and the nonwelded portion of the leading edge to supply filler metal for internal and external fillets.

Immediately before brazing, a cap was placed over the hub end of the blade, and the blade was purged with dry nitrogen for 5 min before entering the furnace. The fixtured blade was brazed in a special circular furnace, 40 ft in diameter, with nine heating and cooling zones (three preheating zones up to 1850 F, a brazing zone at 2080 F, and five cooling zones in which to lower blade temperature to 300 F before removal). The blade remained in each of the zones for 50 min under protection of a prepared nitrogen-base atmosphere containing

10 to 12% carbon monoxide and 10 to 14% hydrogen; dew point was −15 F in the preheating zones, −9 F in the brazing zone, and −6 F in the cooling zones.

The brazed assembly was removed from the brazing fixture and placed in a horizontal box-type hardening furnace. It was quenched in contour quenching dies with the internal cavity pressurized with nitrogen to ensure contact of the camber-sheet surfaces with the die. The blade was tempered in the same die to a final hardness of Rockwell C 30 to 36.

The quality of the brazed joints was evaluated by radiographic inspection, pressure testing at an internal pressure of 90 to 100 psi, and ultrasonic inspection by the immersion technique. Voids in excess of a very small percentage of the total joint area were cause for rejection. Some rejected blades could be rebrazed, but if the rebrazing was unsuccessful, the entire camber sheet had to be replaced.

After the joint quality was approved, internal fillets adjacent to the joint between the camber sheet and the inner rib of the thrust member were shot peened, for improved fatigue properties, with a snorkel-type tube and nozzle inserted through the hub end of the blade.

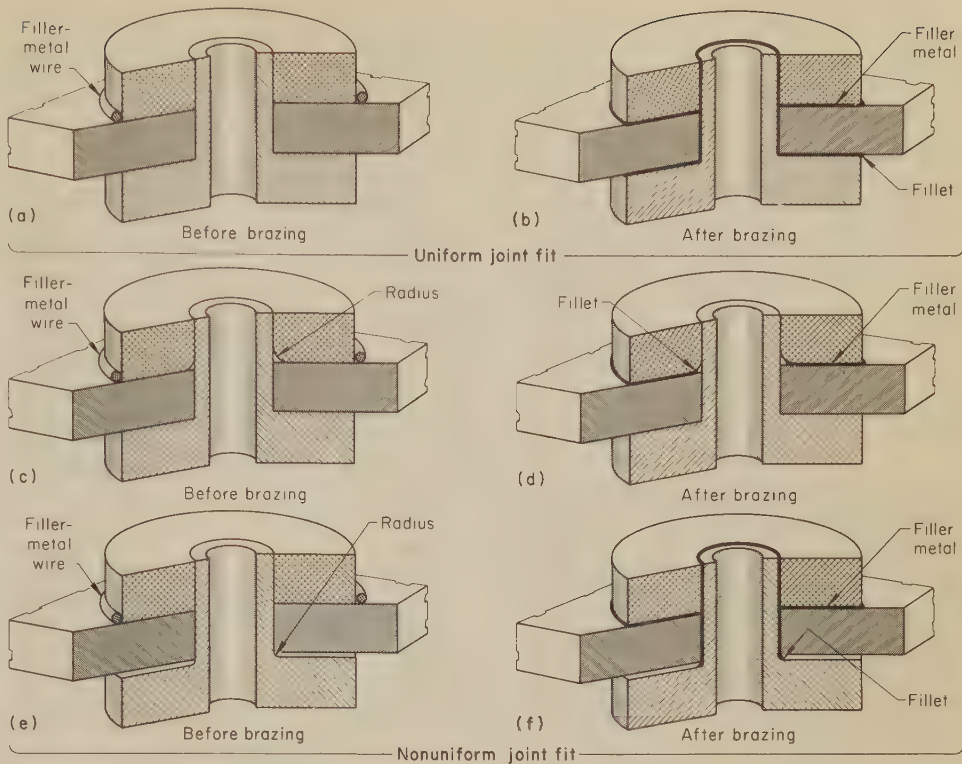
Joint Fit and Design

In brazing, the molten filler metal is drawn by capillary action between closely adjacent, substantially symmetrical surfaces. The distance the filler metal will flow through a joint depends on the clearance between the mating surfaces and on the filler metal used. Molten copper will flow freely and for greater distances than other filler metals in joints with "size-to-size" fit (zero clearance) or an interference fit (negative clearance). The distance of flow of copper increases as joint interference increases, up to the point where the seizing and galling of mating surfaces interferes with capillarity. Conversely, as joint clearance, or gap, is increased, a clearance is reached at which filler-metal flow stops completely. Uniform fit throughout the joint is important, because nonuniform fit will result in nonuniform strength.

Gap Principle. When joint fit is nonuniform, the areas of maximum clearance constitute gaps that interfere with capillary action and impede the flow of filler metal. The effects of uniform joint fit, and of fits containing gaps, on filler-metal flow are shown in Fig. 22. Figure 22(a) shows a joint designed with uniform fit throughout the joint, including the fit at the square internal and external corners. As shown in Fig. 22(b), filler metal from an externally placed wire ring flows uniformly to all parts of the joint, providing a good bond. The joint shown in Fig. 22(c) has uniform fit except at a rounded internal corner. As shown in Fig. 22(d), the gap created by the rounded corner prevents the filler metal from flowing any farther. The joint in Fig. 22(e) has nonuniform fit. The rounded corner and the loose fit at the bottom cause a snug fit at the top. Filler metal flows to most parts of the joint but is blocked at the rounded internal corner (Fig. 22f). The result is an incomplete braze.

The same general principle applies to the design of a joint between a cap and a shell. A joint with uniform fit, as shown in the top view of Fig. 23, results in a uniform bond throughout the joint, whereas a joint with nonuniform fit (or "line contact"), as shown in the bottom view of Fig. 23, results in an incomplete bond and unreliable strength and tightness.

Joint Fit. The amount of clearance or interference provided in a brazed joint directly affects the strength of the joint, although other factors, such as cleanness of the joint, length of the joint, composition of base and filler metals, time at brazing temperature, and subsequent heat treatment, if any, also affect strength. When low-carbon steel components are joined by a copper filler metal, the strength of the joint almost always exceeds the strength of the copper filler metal and, under favorable conditions, is almost equal to the strength of the steel base metal. The effect of fit on joint shear strength is shown by Fig. 24. These data illustrate the desirability of joint fits ranging from zero clearance to in-



Uniform joint fit (a and b) provides a uniform bond throughout the joint. Nonuniform fit, which results in gaps (c, d, e and f), interrupts capillarity and results in incomplete brazing.

Fig. 22. Effects of uniform and nonuniform joint fit on the flow of filler metal in brazing

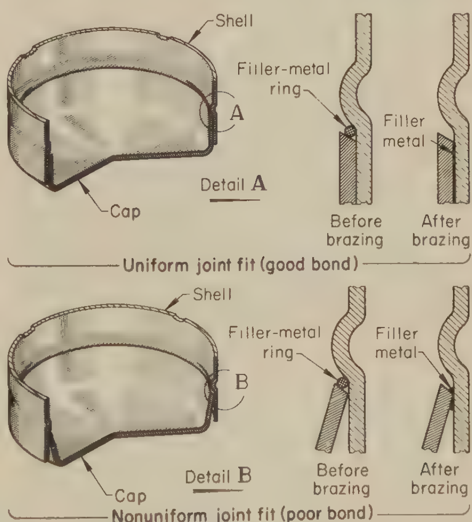
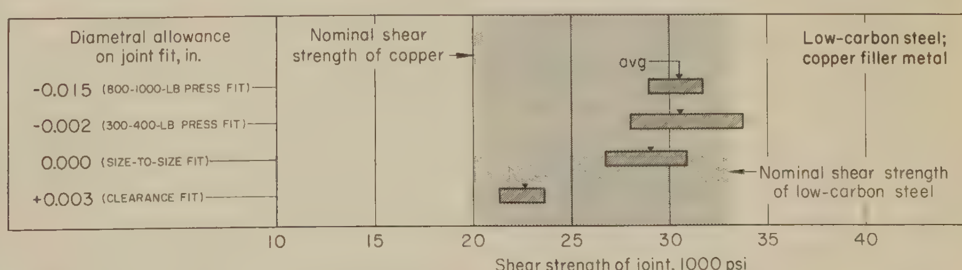
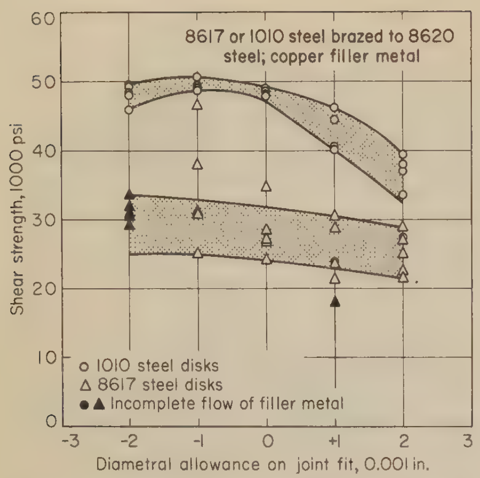


Fig. 23. Effect of joint fit on the bonding of a cap to a shell



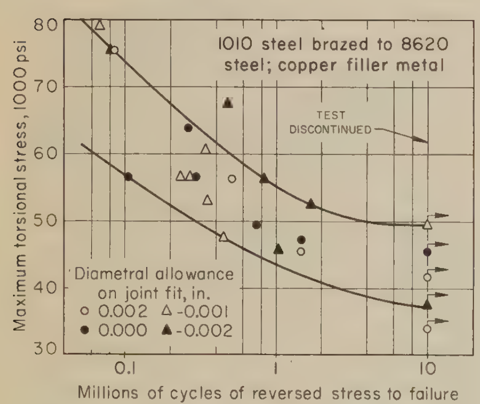
Data are for copper brazed joints in "pull-out" samples made of low-carbon steel. Each sample consisted of a 9⁄32-in.-diam rod copper brazed to a washer 5⁄32 in. thick. After furnace brazing for 20 min, the copper fillets were removed by machining to ensure the accuracy of test results. Ten specimens were prepared for each of the four different degrees of joint tightness. Only six of the ten specimens with the 0.003-in. clearance were tested, because the others exhibited incomplete filling in the joint. (SOURCE OF DATA: George Oswald and Walter Homan)

Fig. 24. Shear strength of copper brazed joints in low-carbon steel as a function of joint fit



Data were taken from tests on parts consisting of an 8620 steel shaft and either an 8617 or 1010 steel disk. Shafts were 9/32 in. in diameter and 4 in. long and were machined to obtain the joint fits shown. Disks were about 2 in. in diameter and 1/4 in. thick with a 0.2500 ± 0.0001-in. center hole. All parts were brazed in an endothermic-exothermic atmosphere, gas carburized at 1500 F for 1 hr, oil quenched, and tempered at 250 F. (SOURCE: William D. Kehr, *Metal Progress*, Jan 1966)

Fig. 25. Shear strength of copper brazed joints between steel components, as a function of joint fit and the composition of the steel



These data, which are the results of tests on brazed joints between 8620 steel shafts and 1010 steel disks, as described with Fig. 25, show that joint fit has essentially no effect on torsional fatigue strength for the range of fits tested. (SOURCE: Same as for Fig. 25)

Fig. 26. Fatigue strength of copper brazed joints as a function of joint fit

terference, although even the joint with 0.003-in. diametral clearance exhibits a strength exceeding the average shear strength of copper. Figure 24 also shows that joints with extreme interference fits are only slightly stronger than joints prepared to a size-to-size fit. Copper filler metal will usually flow through tight fits, provided the brazing temperature and time at temperature are adequate.

For most applications, the recommended diametral fit for copper brazing of low-carbon steel is 0.000 to 0.003-in. interference. High-carbon steels require a slightly looser diametral fit, usually 0.001-in. clearance to 0.002-in. interference. Numerous examples in this article demonstrate the satisfactory use of interference fits and of tight fits approaching zero clearance, but the usefulness of interference fits is limited to assemblies in which the mating surfaces can expand or contract, as required, when pressed together. When the expansion or contraction approaches zero, as is usual with massive components, an interference fit may result in seizing and galling, making it difficult or impossible for copper to flow through the joint.

When maximum joint shear strength is required in brazed assemblies involving low-carbon carbon steels or low-carbon low-alloy steels, one manufacturer of business machines specifies the following diametral allowances on joints between hole walls and tenons to be furnace brazed, using a copper filler metal (wire, foil or paste), and using an endothermic-exothermic gas mixture (71% nitrogen, 15% carbon monoxide, 12% hydrogen, and 2% carbon dioxide, by volume) or dissociated ammonia:

Diameter, in. Hole (+0.0010, —0.0000 in.)	Diameter, in. Tenon (+0.0000, —0.0015 in.)	Diametral allowance on joint fit, in.(a)
0.0625	0.0635	—0.0010 to +0.0015
0.1250	0.1265	—0.0015 to +0.0010
0.2500	0.2520	—0.0020 to +0.0005
0.5000	0.5025	—0.0025 to 0.0000
1.0000	1.0030	—0.0030 to —0.0005
2.0000	2.0030	—0.0030 to —0.0005

(a) Negative allowance is an interference fit; positive allowance is a clearance fit; zero allowance is a size-to-size fit.

These fits were selected after analysis of strength-test data for various nominal joint diameters. For example, Fig. 25 shows the results of shear-strength tests conducted on specimens of the same length with a nominal joint diameter of 0.2500 in. The strongest specimens (1010 steel disks) were those having 0.002, 0.001, or 0.000-in. diametral interference fit. For convenience, the same joint fits were specified for critical assemblies that were subject to alternating torsional loading (torsional fatigue), but test results like those shown in Fig. 26 showed that torsional fatigue strength was essentially independent of joint fit, at least for the range of fits studied.

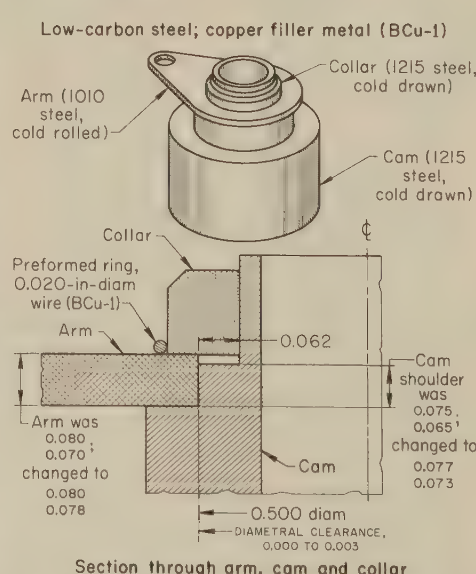


Fig. 27. Assembly for which tolerances on arm stock and cam shoulder were tightened to reduce excessive clearance that prevented adequate flow of brazing filler metal (Example 558)

Low-carbon steels 1010, 8617 and 8620 were used for these tests because they were easier to machine and form than medium-carbon or high-carbon steels and because they were suitable for carburizing after brazing. It was determined that one of the components tested should be a plain carbon steel. As shown in Fig. 25, the specimens with 1010 steel disks had shear strengths as much as 40% greater than those with 8617 steel disks. The reason for this difference was evident when the microstructure of the joints was examined. The joint using 1010 steel disks showed a much deeper penetration of copper on the 1010 steel side of the joint than on the 8620 steel side of the joint. The presence of a chromium-containing oxide film, resulting from incomplete reduction by the furnace atmosphere, probably restricted the diffusion of copper into the 8620 steel. When both components were made of a low-alloy steel, both sides of the joint were affected.

Excessive Joint Clearance. The adverse effect that excessive joint clearance has on the flow of filler metal and the steps taken to correct the difficulty in one application are described in the next example.

Example 558. Tightening of Joint To Reduce Excessive Clearance That Prevented Adequate Flow of Filler Metal (Fig. 27)

Figure 27 shows an assembly in which an arm stamped from cold rolled 1010 steel sheet 0.070/0.080 in. thick (standard tolerance) nested on a 0.065/0.075-in.-high shoulder of a 1215 steel cam. This assembly presented a problem often encountered in brazing assemblies where one component is stamped from steel sheet as-received from the mill — namely, that the thickness of the sheet can vary enough to have an adverse effect on joint clearance. In this assembly, as the thickness of the arm approached the upper allowable limit (0.080 in.) and as the height of the adjacent cam shoulder approached the lower allowable limit (0.065 in.), an annular gap was created beneath the 1215 steel collar that was the third component of the assembly. Under the least favorable conditions, the height of the gap could be 0.015 in., as shown in the sectional view in Fig. 27; the width of the gap was 0.062 in. The copper filler metal, supplied by a 0.020-in.-diam BCu-1 wire, would not flow across and fill a gap of this size; incomplete filling resulted in a joint of unsatisfactory quality.

When the gap was discovered metallographically by sectioning brazed assemblies, it was apparent that tightening of the joint was mandatory. To control the thickness of the arm, tolerances on as-received sheet thickness were changed from standard to select (thickness, 0.078/0.080 in.). The narrowing of tolerances on the cam-shoulder height, to 0.073/0.077 in. (see Fig. 27), also reflected a slight increase in that height. With the maximum possible height of the gap thus reduced, the filler metal could flow past the gap area, down the vertical joint between the cam and the arm, and through the horizontal joint between them. The cam-arm joint was the principal load-carrying joint.

The three components were vapor degreased before assembly and were brazed at 2070 F for 12 min in a 100-kw, mesh-belt (12-in. wide) conveyor furnace in an endothermic atmosphere. Production rate was 250 assemblies per hour. The brazed assemblies were subsequently carburized.

Brazed assemblies rejected for inadequate joint penetration were salvaged by inverting the assembly, placing a filler-metal ring along the outside corner of the joint between the arm and the cam, and rebrazing to fill the cam-arm joint with the ad-

ditional filler metal. Unassembled components with the old tolerances were salvaged by assembling the components with a ring of filler metal in the gap area in addition to the ring at the arm-collar joint, thereby using two sources of copper filler metal in the brazing operation.

Factors Affecting Fillet Size. Provided the volume of filler metal is controlled, joint clearance or interference can, within limits, serve to control the size of fillets. With a fixed volume of filler metal available to the joint, an increase in joint clearance will decrease top-fillet size and increase bottom-fillet size, and a decrease in joint clearance will have the opposite effect. Also, when joint clearance or interference is fixed, an increase or decrease in the volume of filler metal will have a similar effect on fillet size.

With brazed joints, fillet size should be called out on drawing notes only if it is significant to the function of the brazement — large fillets do not necessarily increase joint strength.

The next two examples describe applications involving control of fillet size.

Examples 559 and 560. Controlling the Size of Brazed Fillets

Example 559 — Arm-Hub-Stud Assembly (Fig. 28). In copper brazing the assembly shown in Fig. 28, service requirements made it mandatory to limit the size of the fillet of filler metal at the top of the joint between the stud and the arm to a maximum fillet leg of 0.015 in Diametral clearance between the stud and arm was 0.000 to 0.002 in. It was determined that filler metal in the form of a preformed ring of 0.015-in.-diam copper wire (BCu-1) provided enough filler metal to fill the joint, without exceeding the fillet-size limitation.

Fillet size was not critical at the joint between hub and arm, and an interference fit of 0.0005 to 0.0030 in. and a 0.018-in.-diam filler-metal wire were selected.

As indicated in Fig. 28, the hub and stud were made of 1215 steel, and the arm was made of 1010 steel. The components were degreased before assembly and were brazed at 2070 F in a 100-kw, mesh-belt conveyor furnace (12-in.-wide belt). Heating time at 2070 F was 9 min, and production rate was 1750 assemblies per hour. An endothermic atmosphere was used in the furnace.

Example 560 — Shaft-and-Plate Assembly (Fig. 29). The fillet of filler metal at the top junction of the shaft and the plate of the assembly shown in Fig. 29 was required not to exceed 0.010 in. when measured with a ring gage after nickel plating (0.0003 in. thick). The shaft, made of leaded low-carbon steel, and the low-carbon steel plate were vapor degreased before they were assembled and were held by riveting, as shown in Fig. 29. Diametral clearance between components was held between 0.001 and 0.005 in. The filler metal was in the form of a preformed ring made of 0.013-in.-diam copper wire (BCu-1), and was preplaced at the joint, as shown in Fig. 29. This volume of filler metal was enough to completely fill the joint without forming fillets larger than allowed.

The assembly was brazed in an electric pusher-type furnace at 2050 F, in a nitrogen-base atmosphere (30% CO and 16% H_2). Brazing time was 15 min, and production rate was 150 assemblies per hour.

Notched Joint for Venting. Although joints with interference fits are common with copper brazing because of the exceptional flow characteristics of copper, flow into blind passages may sometimes be hindered by entrapped air. Venting of a joint with interference fit can promote normal flow, as in the following example.

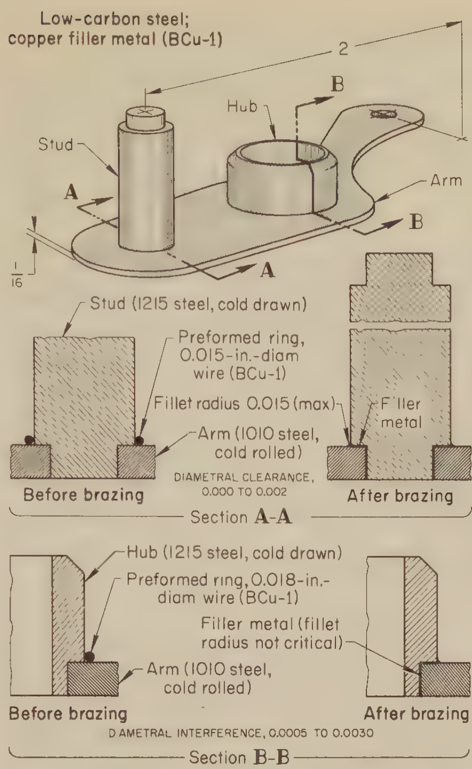


Fig. 28. Assembly for which size of filler-metal fillet in one of two brazed joints was controlled by use of smaller-diameter wire, and by designing joint with clearance instead of interference (Example 559)

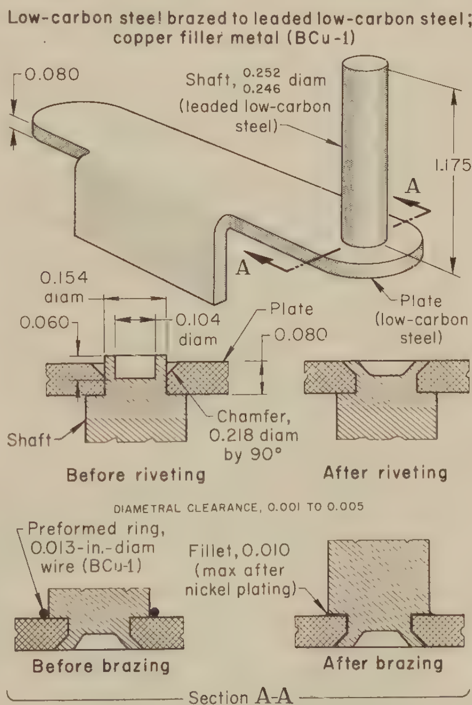


Fig. 29. Brazed riveted assembly for which size of filler-metal fillet was controlled by use of a preformed ring of filler wire of proper diameter (Example 560)

Example 561. Venting an Interference-Fit Joint To Promote Flow of Filler Metal (Fig. 30)

When sectioned samples of the brazed multiple-gear assembly shown in Fig. 30 revealed incomplete penetration of the joints, it was determined that the cause was air entrapped in the joint and that the original joint design (section A-A in Fig. 30) required modification in the form of venting. Venting was achieved by notching the internal diameters of the gears at two locations, 180° apart (see section B-B in Fig. 30), in a blanking die. Without a change in joint fit (0.0005 to 0.0030-in. diametral interference), which was required in order to maintain concentricity, or the location of the filler-metal preforms (rings of 0.015-in.-diam BCu-1 copper wire), venting sufficed to relieve entrapped air, thereby allowing unhindered flow of filler metal to fill the joints. Joint filling was known to be complete when copper was visible at the side of the joint opposite that where the filler-metal ring was placed.

The components, of low-carbon steel, were vapor degreased before assembly and were brazed in a 100-kw, mesh-belt conveyor furnace (12-in.-wide belt) at 2070 F, in an endothermic atmosphere. Brazing time was 10 min, and production rate was 3500 assemblies per hour.

Joint Design. In general, lap joints are preferred for brazing. These joints depend for their strength on penetration between close, conforming surfaces, rather than on external fillets; the joints are usually intended to be stressed in shear. A rule of thumb is to make the length of the joint at least three times the thickness of the thinnest section.

Joints should be designed especially for brazing. Six joint designs commonly used for arc welding are compared with their counterparts for brazing in Fig. 31. Any of the joints shown for arc welding could be joined by brazing, but at great sacrifice in strength. Actually, each of the joint designs shown in Fig. 31 as being used for brazing is a lap joint.

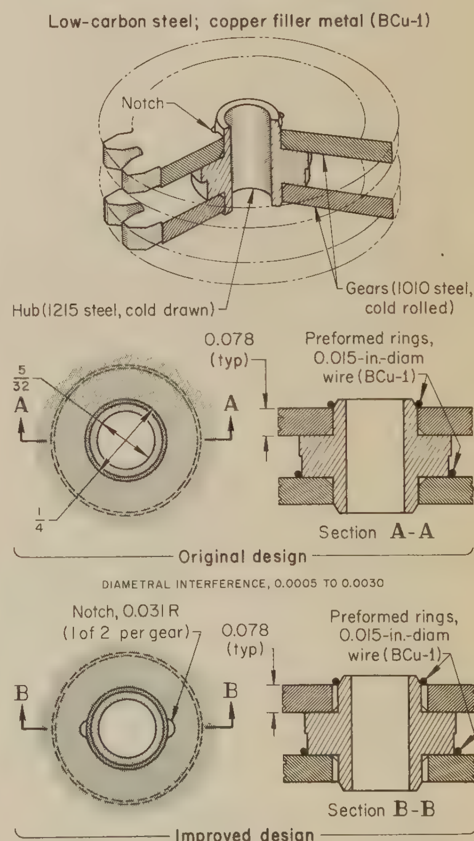


Fig. 30. Multiple-gear assembly to which notches were added to vent the joint and allow complete flow of brazing filler metal through the joint (Example 561)

Table 5. Compositions, Solidus and Liquidus Temperatures, and Brazing-Temperature Ranges of Silver Alloy Filler Metals Used in Furnace Brazing (AWS A5.8)

AWS classification	Composition, % Ag	Cu	Zn	Cd	Ni	Temperature, F Solidus	Liquidus	Brazing
BAg-1	44 to 46	14 to 16	14 to 18	23 to 25	....	1125	1145	1145 to 1400
BAg-1a	49 to 51	14.5 to 16.5	14.5 to 18.5	17 to 19	....	1160	1175	1175 to 1400
BAg-3	49 to 51	14.5 to 16.5	13.5 to 17.5	15 to 17	2.5 to 3.5	1170	1270	1270 to 1500
BAg-4	39 to 41	29 to 31	26 to 30	....	1.5 to 2.5	1240	1435	1435 to 1650
BAg-5	44 to 46	29 to 31	23 to 27	....	....	1250	1370	1370 to 1550

In designing for brazing, butt joints are generally avoided. If the use of a butt joint is unavoidable, the entire assembly must be designed to ensure that there will be no deflection or bending stresses at the brazed joint. Concentration of bending stresses at the joint will cause the brazed filler metal to tear, especially if the base metal has a higher modulus of elasticity than the filler metal. In brazing steel with a copper filler metal, the difference in elastic modulus is pronounced (30 million vs 17 million psi).

Change in Section Thickness. When a brazed assembly is subjected to bending stresses or fatigue, an abrupt change in section thickness in the joint area will promote failure at the joint, just as in a welded joint. This type of failure is caused by the relative flexibility of the thin section and rigidity of the heavy section. Failure can be avoided by tapering the heavy section in the joint area, thereby providing the two components with approximately equal stiffness at the point where failure would otherwise occur. This reduction in section also facilitates brazing, because it provides more uniform heating, uniform clearance, and uniform filler-metal flow.

Surface Condition. The importance of cleaning as a preparatory step before brazing is discussed in the section on Cleaning and Surface Preparation for Brazing. Satisfactory flow of filler metal is highly dependent on the cleanness of the joint area.

Surface finish also affects capillarity. The relatively smooth surfaces that are obtained by polishing or fine grinding are less readily wetted by molten filler metal than are rough surfaces. Therefore, it is sometimes advisable to roughen the mating surfaces, such as by rubbing with 60 to 100-grit silicon carbide papers, to prepare them for brazing. A grit blasted or shot blasted surface is most readily wetted. Sand blasting is not recommended, because embedded sand particles interfere with wetting action. Any surface treatment that involves the use of aluminum oxide or titanium oxide abrasives should be avoided, because these abrasives deposit a surface contaminant a few microns thick on the parts, which generally inhibits wetting.

Brazing With Silver Alloy Filler Metal

Because heat input to the work is localized in torch and induction brazing of steel, the lower melting and brazing temperatures of a silver alloy filler metal are distinctly advantageous; less often are these advantages a significant factor in furnace brazing of steel. Consequently, the use of silver alloy filler metals is generally limited in furnace brazing to applications for which the copper filler metals or the high brazing temperatures (2000 to 2100 F) they require are not suited. Among these applications are the following:

1. Brazing a carbon or low-alloy steel to a stainless steel or to a nonferrous metal or alloy such as copper or brass
2. Brazing with joint clearances that are larger than those permitted in copper brazing
3. Brazing an assembly that will distort excessively or suffer a loss of desirable properties at the temperatures used in copper brazing
4. Brazing subsequent joints in a copper brazed assembly — a practice referred to as step brazing.

Types and Forms of Filler Metal. Five silver alloy filler metals generally used in furnace brazing are identified in Table 5, including chemical compositions, and solidus, liquidus and brazing temperatures.

BAg-1 and BAg-1a filler metals are used in furnace brazing carbon steel to carbon steel, to austenitic stainless steel, and to copper or copper alloys. These filler metals are quaternary silver-base alloys containing copper, zinc and cadmium. They are free-flowing, with a relatively low brazing-temperature range. In furnace brazing, BAg-1a is often preferred to the less costly BAg-1 because of its higher silver and lower cadmium contents, which render it less susceptible to joint porosity.

Silver alloy filler metals that contain substantial percentages of cadmium were originally intended for use in torch or induction brazing, not furnace brazing. There is a large loss of cadmium during furnace brazing and the resulting joint metal will be considerably different in cadmium content than that in a joint brazed by torch or induction. However, the cadmium-bearing filler metals are widely used for furnace brazing.

The same combinations of metals and alloys can be furnace brazed with BAg-5 filler metal as with BAg-1 and BAg-1a filler metals. BAg-5 is a ternary silver-base alloy with a considerably higher brazing-temperature range. It is used in applications where a free-flowing filler metal is not desirable because of joint design or other factors. Because it is cadmium-free, it is used in applications where cadmium is prohibited, as in food-handling and pharmaceutical equipment.

Filler metals BAg-3 and BAg-4 contain nickel, and are used in furnace brazing steel to ferritic or martensitic stainless steels containing chromium as the principal alloying element and little or no nickel. Joints in these steels are susceptible to interface corrosion in water or moist air unless they are brazed without flux, using a nickel-containing filler metal. BAg-4 is used when a wider range between solidus and liquidus is required than that of BAg-3. Both alloys are also used in brazing carbide tips to steel tools.

Fluxes. When filler metals BAg-1, BAg-1a, BAg-3, BAg-4 and BAg-5 are used, a flux is required in furnace

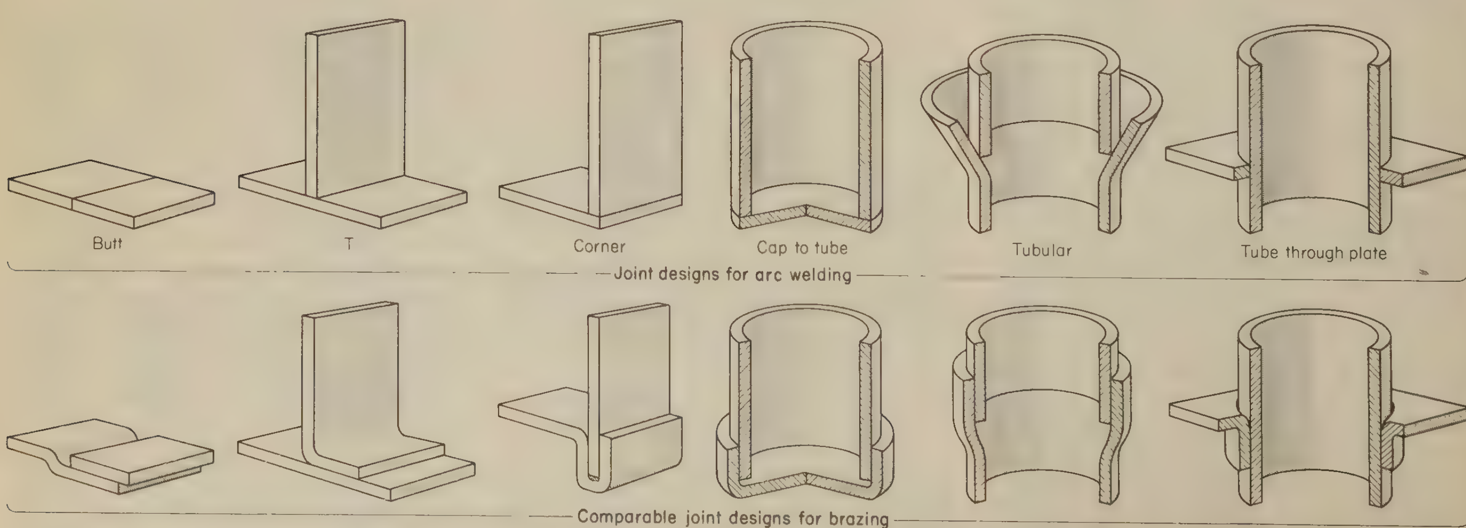


Fig. 31. Comparison of joint designs commonly used in arc welding and comparable designs used in brazing (H. R. Brooker and E. V. Beatson)

brazing steel to steel, or steel to a dissimilar metal. Without corroding the base metals, the flux serves to reduce surface oxides, ensuring that filler metal will flow and that base metals will be satisfactorily wetted by it.

Flux of AWS type 3A satisfies these requirements and is widely used in furnace brazing with silver alloy filler metals. It contains boric acid, borates, fluorides, fluoborate, and a wetting agent; it is effective in furnace brazing — with protective atmosphere — within the temperature range of 1050 to 1600 F. It is available as a paste or powder, and can be mixed with water, alcohol, or monochlorobenzene for thinning to a liquid consistency. Depending on consistency, flux is applied by brushing or spraying, or by metering from a gun.

Flux residues must be completely removed from assemblies after brazing. The fluoride-type fluxes generally used in silver brazing develop residues that are hygroscopic and corrosive. Methods of removing flux residues from base metals are discussed on pages 630 and 631 in the article on Torch Brazing.

Joint Clearance. Recommended diametral joint clearances for brazing with silver alloy filler metals range from 0.002 to 0.005 in. This range takes into account the differences in the flow characteristics and liquidus temperatures of the various silver alloy filler metals. Size-to-size (zero clearance) and interference fits are not recommended, although joints with interference fits have been successfully silver brazed (see Example 562).

Furnaces. The batch-type box furnaces and mesh-belt conveyor furnaces used in copper brazing are generally suitable for brazing with silver alloy filler metals, provided that the furnaces can maintain satisfactory temperature uniformity in the lower ranges.

Because of their chemical activity, brazing fluxes are potentially damaging to furnace components such as heating elements, mesh belts, rolls, hearth plates, and refractories. They temporarily reduce protective oxides, until their activity is exhausted, and then the oxides re-form. The most severe damage occurs when fluxes are permitted to make direct contact with furnace components. It is common practice to equip silver brazing furnaces with alloy muffles to protect furnace components against flux attack, but some plants report that the use of muffles is unnecessary. Assemblies are usually placed on catch trays that collect flux drips throughout the brazing cycle. The damaging effects of flux constituents in volatilized form are apparently modified to a considerable extent by dilution with the protective furnace atmosphere and by diversion to a venting system.

Protective Atmospheres. The protective atmospheres most commonly used in furnace brazing with silver alloy filler metals are rich exothermic gas, endothermic gas, dissociated ammonia, and dry hydrogen. Even when a flux is used, an atmosphere is usually employed, to minimize or prevent oxidation and discoloration of the base metals and to ensure that the flux performs its functions.

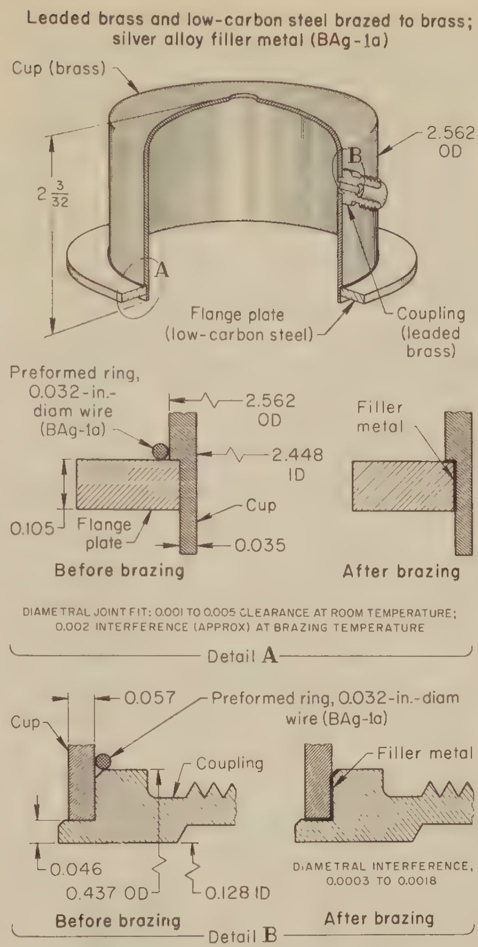


Fig. 32. Brass and steel bellows-housing assembly that was furnace brazed in an endothermic atmosphere, using a silver alloy filler metal and flux (Example 562)

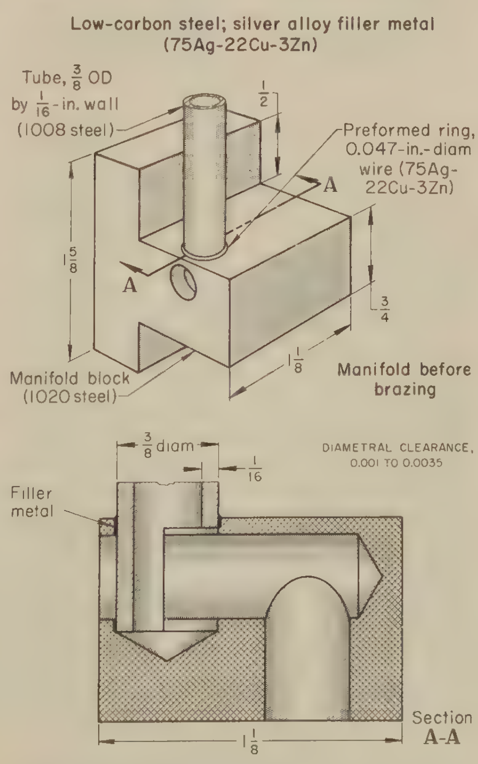


Fig. 33. Manifold assembly that was furnace silver brazed, using a protective atmosphere of dissociated ammonia and no flux (Example 563)

Exothermic and endothermic atmospheres are less expensive than dissociated ammonia or dry hydrogen; they are used in furnace brazing of steel to steel or to oxygen-free copper or copper alloys, using a flux and BAg-1a or BAg-5 filler metal.

Provided dissociation is complete (100%), dissociated ammonia can be used in nearly all furnace brazing applications involving the use of silver alloy filler metals. If dissociation is less than 100%, however, the atmosphere may promote nitrogen pickup (nitriding) in carbon and low-alloy steels.

The use of dry hydrogen as a protective atmosphere is generally limited to fluxless brazing applications in which the most strongly reducing atmosphere available is required to ensure removal of surface oxide and the satisfactory flow of filler metal. The hydrogen must be extremely dry (dew point, −60 F or less) for maximum effectiveness.

Examples of Silver Brazing. The two examples that follow illustrate the use of an endothermic gas and dissociated ammonia as protective atmospheres for furnace brazing, using silver alloy filler metals. The first of these examples also illustrates the use of BAg-1a filler metal with flux, and the second deals with fluxless brazing, using a special ternary silver alloy filler metal.

Example 562. Silver Brazing Steel to Brass in an Endothermic Atmosphere, Using Flux (Fig. 32)

The bellows housing shown in Fig. 32 was brazed at 1350 F in an electric box furnace in an endothermic atmosphere, using BAg-1a silver alloy filler metal and a type 3A flux. The low-melting silver filler metal was selected to avoid damaging the brass parts of the assembly. An endothermic atmosphere was selected because of availability and cost.

As shown in Fig. 32, the housing assembly consisted of a deep drawn brass cup, a leaded brass coupling, and, outside the critical area requiring corrosion resistance, an inexpensive low-carbon steel flange plate. Before assembly, the brass components were bright dipped and the steel plate was vapor degreased. The coupling was press fitted into the side of the cup, and a preformed ring of 0.032-in.-diam BAg-1a wire was snap fitted onto the shoulder of the coupling. Then the brass cup was seated in the hole of the flange plate, and a preformed ring of 0.032-in.-diam BAg-1a wire was snap fitted to the cup. Flux was applied to the joint areas, and assemblies were placed on furnace trays in lots of 30 per tray.

Each trayload was pushed into the hot chamber of the furnace, where it remained, in an endothermic atmosphere, for 10 min. Because the liquidus temperature of the filler metal was 1175 F, the furnace temperature of 1350 F provided a slightly accelerated heating rate. At the end of the heating cycle, the tray was pushed into an adjacent cooling chamber, where the assemblies were again protected by an endothermic atmosphere. For safety, atmosphere in both heating and cooling chambers was maintained at positive pressure, and flame curtains were kept burning at entrance and exit ends of the furnace.

Production rate was 180 assemblies (or 360 brazed joints) per hour. Brazing costs per assembly were as follows:

BAg-1a preform (large)	$0.0430
BAg-1a preform (small)	0.0063
Total filler-metal cost	$0.0493
Assemble and flux (2.12 min)	$0.0795
Brazing labor	0.0139
Total labor cost	$0.0934
Total per assembly	$0.1427

After brazing, the flux residue was removed and brazed assemblies were cleaned by a combination of pickling and bright dipping. (Although the endothermic atmosphere minimized the amount of cleaning required, it did not completely eliminate the need for cleaning.)

Example 563. Brazing of Steel in Dissociated Ammonia, Using a Ternary Silver Alloy Filler Metal and No Flux (Fig. 33)

Figure 33 shows a hydraulic manifold assembly consisting of a 1008 steel tube and a 1020 steel manifold block containing machined passages for the flow of oil. The assembly did not lend itself to interference fits, characteristic of copper brazing, nor could a flux residue be readily cleaned from the blind internal passages. Consequently, diametral joint clearances were established at 0.001 to 0.0035 in., and a ternary silver alloy that did not require flux was selected as the brazing filler metal. This alloy (75% Ag, 22% Cu, 3% Zn), with a liquidus temperature of approximately 1500 F, developed satisfactory wetting characteristics with the reducing potential of a dissociated ammonia atmosphere.

The assemblies were brazed in a mesh-belt conveyor furnace heated to 1600 F, using the silver alloy filler metal in the form of wire rings. The brazing time at 1600 F was 12 min, during which period it was estimated that assemblies were heated to between 1500 and 1550 F. Production rate was 60 assemblies per hour.

Furnace Brazing vs Other Brazing Processes

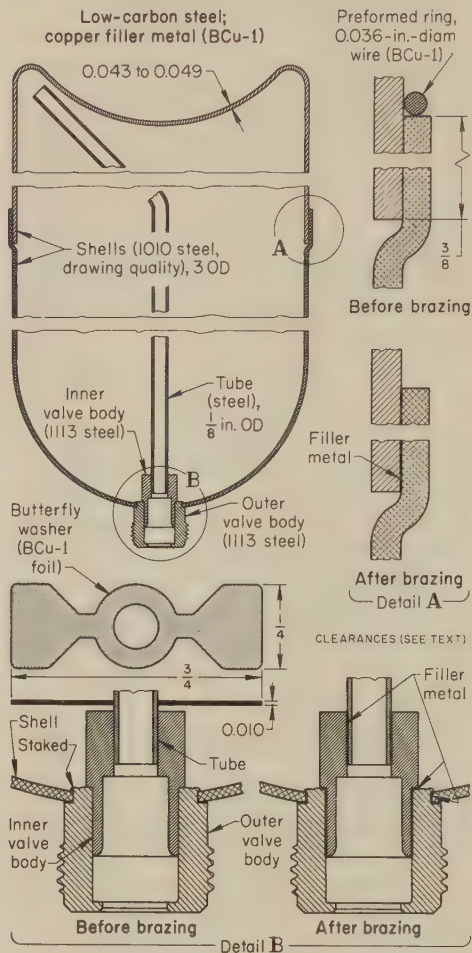
Among the advantages of furnace brazing are the abilities to achieve high production rates, to provide a high degree of reproducibility of results, and to use inexpensive copper filler metals and inexpensive protective atmospheres that generally are not suited to other brazing processes, particularly induction and torch brazing.

The five examples that follow describe production applications in which furnace brazing was selected in preference to, or replaced, induction brazing or torch brazing. In all applications, the adoption of furnace brazing resulted in the substitution of a copper filler metal for a silver alloy filler metal. In one application, the cost of furnace brazing with a silver alloy filler metal was estimated before furnace brazing with a copper filler metal was approved and adopted. In four of the five applications, the atmosphere used for furnace brazing was an exothermic-base gas mixture.

Example 564. Cost Reduction and Product Improvement Resulting From Use of Furnace Copper Brazing Instead of Induction or Furnace Silver Brazing (Fig. 34)

When the steel aerosol-container assembly shown in Fig. 34 was brazed by induction, using BAg-1 silver alloy filler metal and flux, flux residue, which clogged valve and tube passages, was difficult and expensive to remove and, when not removed completely, absorbed moisture and was a potential source of corrosion. Moreover, a large percentage of the induction brazed containers leaked, because on a large production scale, it was difficult to provide the surfaces to be brazed with the degree of cleanness and uniformity of fluxing needed to prevent leaks.

On the basis of an engineering and cost study, it was determined that brazing the assembly in a furnace, in a protective atmosphere, using a copper filler metal (BCu-1) that did not require a flux, would eliminate the passage-clogging and cleaning problems, improve joint quality, increase production rate, and reduce brazing costs. As part of the same study, costs were estimated for furnace brazing using BAg-1 silver alloy filler metal. Actual costs were established for furnace brazing with



Item	Silver brazing (est)	Copper brazing (actual)
Annual Costs per Furnace		
Filler metal	\$180,300(a)	\$ 9,680(b)
Furnace power(c)	4,910	7,420
Atmosphere gas(d)	2,100	2,100
Maintenance	24,335	25,350
Furnace investment	10,500(e)	11,000(f)
Interest(g)	2,110	2,190
Taxes and insurance(h)	2,110	2,190
Labor and overhead(j)	142,000	119,000
Total annual cost per furnace	\$368,365	\$178,930
Total cost per assembly(k)	\$0.1316	\$0.0639
Saving by copper brazing:		
Annual, per furnace		\$189,435
Per assembly		\$0.0677

(a) For BAg-1 wire at \$1.12 per troy ounce, foil at \$1.18 per troy ounce. (The costs are lower than those given on page 600 because of the large quantity used.) (b) For BCu-1 wire at 89¢ per pound, foil at \$1.20 per pound. (c) At 1¢ per kilowatt-hour. (d) Coke-oven gas at 75¢ per 1000 cubic feet. (e) \$84,500 (furnace cost) divided by 8 (years of depreciation). (f) \$88,000 (furnace cost) divided by 8 (years of depreciation). (g) 5% of half of furnace cost. (h) 2½% of furnace cost. (j) At \$8.50 per hour for skilled labor, \$5.70 per hour for semiskilled labor, including overhead. (k) Based on annual production of 2.8 million assemblies per furnace.

Fig. 34. Furnace brazed aerosol container for which copper was used instead of silver alloy as the filler metal, on the basis of the estimated cost saving shown in the table (Example 564)

copper filler metal after the furnace brazing operation was adopted. Both sets of costs are shown in the table that accompanies Fig. 34.

In this cost comparison, furnace costs (investment, interest, and taxes and insurance) and costs for power consumption and maintenance are higher for copper brazing because of the higher brazing temperature, but the estimated maintenance cost for silver brazing is high because of anticipated flux attack on alloy trays, rolls and heating elements. Labor cost for silver brazing is higher because of the need for fluxing and subsequent cleaning. Excluded from the comparison are the costs of forming the rings of filler-metal wire and stamping the butterfly washer from filler-metal foil (which would have been nearly equal for both filler metals), and the costs for flux and for reworking of rejects. The major item in the comparison is cost of the two filler metals, and it is apparent that the use of copper offered a substantial over-all cost saving.

The furnace equipment that replaced induction brazing consisted of two 180-kw electrically heated roller-hearth furnaces, with door openings 30 in. wide by 13 in. high, heating chambers 9 ft long, and cooling chambers 30 ft long. Furnaces were supplied with a rich exothermic atmosphere generated by two 1500-cfh generators from coke-oven gas.

Before being furnace brazed, the 1010 steel shells of the container were washed with hot caustic and rinsed well, and the inner and outer valve bodies, machined from 1113 steel, were vapor degreased. The joint between the shells had diametral interference of 0.002 to 0.010 in., and ⅜-in. overlap. The inner valve body was knurled for a press fit in the outer valve body. The outer body was free fitted into the shell and was staked in four places. The tube was press fitted into the inner valve body and was flattened slightly below a copper butterfly washer, to hold the washer in place. The butterfly washer, which served as filler metal in the valve-body area, was made of 0.010-in.-thick commercially pure copper foil. Filler metal for the joint between the shells was a preformed ring of 0.036-in.-diam commercially pure copper wire.

The brazing cycle consisted of heating for 12 min at 2100 F, and cooling for 40 min. The assemblies were moved through the furnace on trays, each tray containing 54 assemblies. One skilled operator controlled both furnaces, and nine semiskilled workers were required for assembly. Production rate per furnace was 702 assemblies per hour. Power consumption was 157 kwhr per hour per furnace; each atmosphere generator consumed 675 cubic feet of coke-oven gas per hour.

Examples 565, 566 and 567. Change From Manual Torch Brazing to Furnace Brazing To Increase Production (Fig. 35)

When furnace brazing with copper filler metal replaced manual torch brazing with a silver alloy filler metal, production rates for a tube-and-lever assembly (Example 565), a can-opener blade assembly (Example 566), and a plate-and-bushing assembly (Example 567) increased by as much as 500%. As shown in Fig. 35, the components of the tube-and-lever and the can-opener blade assemblies were assembled by staking before furnace brazing. Staking helped to compensate for the large joint clearances, which were designed initially for brazing with silver alloy filler metal. The plate-and-bushing components were assembled by fixturing, the fixture consisting of a steel strap bent to the U-shape shown in Fig. 35. Each fixture supported three or four assemblies.

All three assemblies were brazed at 2000 to 2010 F in a conveyor furnace with a 12-in.-wide mesh belt and an exothermic atmosphere. The filler metal was supplied by preformed rings of BCu-1 copper wire, 0.020 or 0.030 in. in diameter, depending on

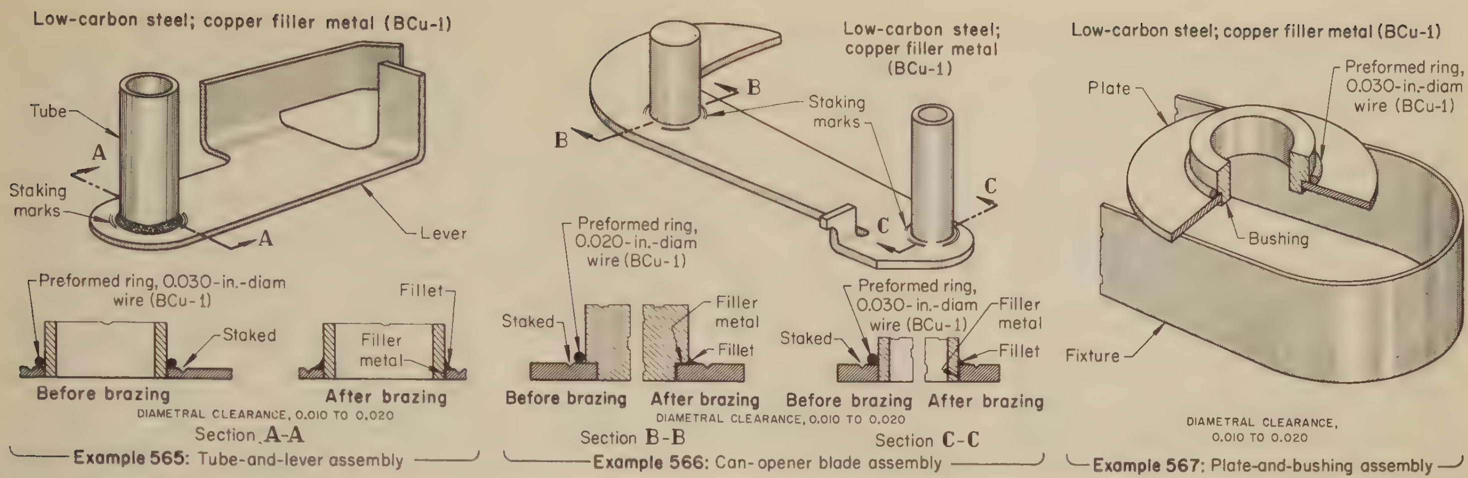


Fig. 35. Three steel assemblies for which furnace brazing was substituted for manual torch brazing (Examples 565, 566 and 567)

joint requirements. Furnace-belt speed was adjusted for each of the three assemblies to ensure full joint penetration and the formation of a brazed fillet.

Example 568. Production-Rate Increase of 128% With Change From Automatic Torch Brazing to Furnace Brazing (Fig. 36)

When the throttle-linkage assembly shown in Fig. 36 was brazed in an automatic, multiflame torch brazing machine, using a silver alloy filler metal, production rate was 240 assemblies per hour. A change to furnace brazing, using a copper filler metal, resulted in a production rate of 548 assemblies per hour — an increase of 128%.

Components were assembled for brazing by placing the 12L14 steel shaft in a nesting fixture and pressing the 1010 steel lever into position over the shaft with an arbor press. For torch brazing, the operator placed a preformed ring of silver alloy filler metal over the shaft after the components were assembled, and applied flux to the joint with a paintbrush. The assembly was then placed in a ceramic fixture on a chain conveyor that carried it past several gas burners that preheated the base metal and melted the filler metal. The brazed assembly was unloaded automatically.

For furnace brazing, a copper filler-metal paste was applied to the joint area by means of an automatic, air-actuated paste dispenser that metered the amount applied. Assemblies were then placed on a stainless steel plate that then was placed on the furnace conveyor belt. Assemblies were brazed at 2100 F in a 71-kw, mesh-belt conveyor furnace (12-in.-wide belt), in an endothermic atmosphere (65 F dew point) prepared from natural gas. Time at brazing temperature was about 10 minutes. The furnace used was a muffle furnace that was equipped with two heating zones and two water-cooled cooling chambers.

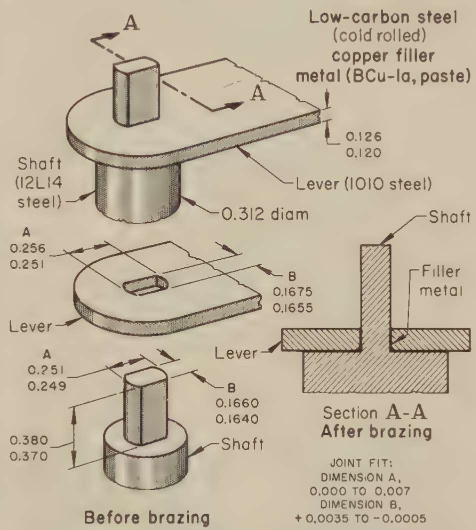


Fig. 36. Throttle-linkage assembly for which furnace brazing was substituted for automatic, multiflame torch brazing to increase production (Example 568)

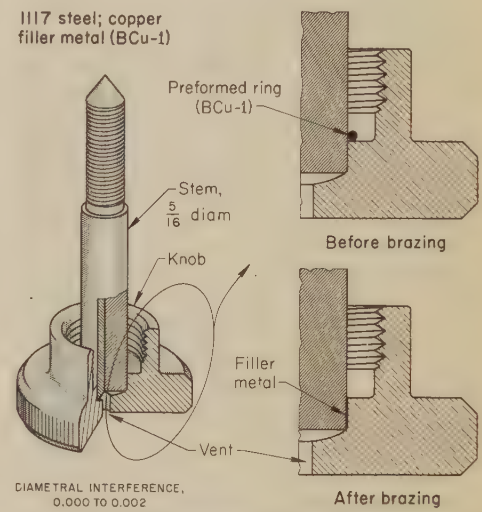


Fig. 37. Shutoff-valve stem that was changed from a one-piece product to a brazed, two-piece, automatic-bar-machine product to save material and machining time (Example 569)

Furnace Brazing To Supplement, Modify or Replace Other Fabricating Processes

From a design standpoint, furnace brazed assemblies are of two general types: (*a*) those designed initially for brazing, and (*b*) those redesigned for brazing for any of several reasons, including product improvement, increased production rate, ease of fabrication, and cost. Nearly all of the examples of practice considered in previous sections of this article have dealt with assemblies that were designed initially for brazing, but many high-production parts have been redesigned to permit the substitution of furnace brazing for other fabricating processes. Examples in which assemblies were redesigned for brazing are considered in this section; each describes a brazing application that was adopted to supplement, modify, or replace another fabricating process.

Machining and Brazing. Furnace brazing can sometimes be used in combination with machining to conserve material and machining time and to simplify the fabrication of complex shapes. Usually, this entails the subdivision of a single, complex part into two or more relatively simple elements that can be assembled and joined by furnace brazing. Applications in which machining and furnace brazing were judiciously combined to simplify complex parts are described in the first two of the three examples that follow. The third example describes the combining of furnace brazing with machining to reduce the fabrication cost of a relatively simple part.

Example 569. Production by Machining and Furnace Brazing That Saved Material and Machining Time (Fig. 37)

Originally, the shutoff-valve stem shown in Fig. 37 was machined in one piece from 1⅛-in.-diam 1117 steel bar stock, 2½ in. long and weighing 11 oz. As made in one piece, the valve stem was too complicated to be completed in an automatic bar machine, so production rate was slow and highly skilled labor was required to complete the part in a secondary machining operation.

When the knob and stem were redesigned as separate components to be joined by furnace brazing, both components were simple enough to be turned in automatic bar machines, reducing machining time and saving 7½ oz of stock, or about two-thirds of the total weight of the original blank.

When made as a separate component, the knob was turned from a 9⁄16-in. length of 1⅛-in.-diam 1117 steel bar stock. The stem was turned from a 2½-in. length of a 5⁄16-in.-diam bar of the same steel. As shown in Fig. 37, the components were machined for a light press fit (0.000 to 0.002 in. interference).

Before assembly, the components were cleaned by immersion in a caustic bath. They were then assembled, and BCu-1 copper filler metal in the form of a wire ring was placed over the stem, as shown in Fig. 37. Assemblies were loaded on 17-by-30-in. trays in lots of 300 for entry into the furnace.

Assemblies were brazed at 2050 F in an electric box furnace, in an exothermic atmosphere. Brazing time was slightly less than 12 min (time in the high-heat chamber), and one operator processed 1560 assemblies per hour. At this rate of production, the value of the steel saved by combining machining and furnace brazing amounted to more than $100 per hour.

Example 570. Simplifying Fabrication by Combining Machining and Furnace Brazing (Fig. 38)

Several features in the design of the fuel-injection pump-nozzle holder shown in Fig. 38 made it difficult and expensive to fabricate in one piece. It required an internally threaded round base to adjoin a smaller hexagonal section — a combination requiring several different machining operations and different machines. In the upper portion, it also required six 1/32-in.-diam holes extending from an outer shoulder to an inner recess.

To simplify fabrication and reduce cost, the nozzle holder was machined as two separate pieces, both of 1117 steel bar stock, in automatic bar machines. The threaded base was machined from 1-in.-diam round bar, and the upper portion, from ¾-in. hexagonal bar. The internal cavity was made by counterboring the hexagonal stock, and the six holes were drilled through the hexagonal body to connect with the counterbored recess.

A shoulder was machined on the base, and a matching counterbore on the upper portion, to nest the upper portion on the base. The nesting surfaces were machined to obtain a light interference fit (0.000 to 0.002 in. on diameter), for positive location and good flow of copper filler metal. A preformed hexagonal ring of BCu-1 copper wire was slipped over the hexagonal section to complete the assembly (see Fig. 38).

Assemblies were brazed in an electric box furnace at 2050 F, in an exothermic atmosphere. Production rate was about 1500 assemblies per hour.

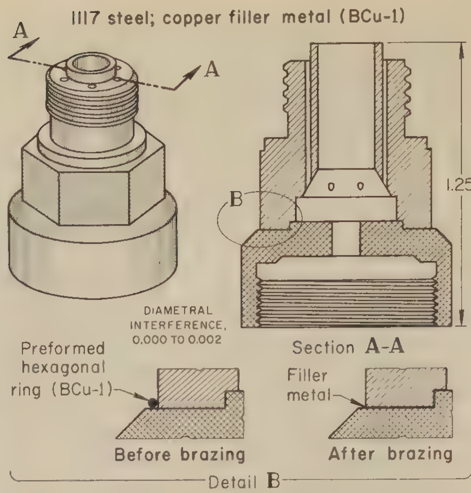


Fig. 38. Fuel-injection pump-nozzle holder that was produced as a brazed assembly of two components to simplify machining (Example 570)

Brazing Instead of Mechanical Fastening. Bolting, riveting, and staking are often replaced by brazing for applications where mechanically fastened assemblies are likely to be loosened by vibration. The example that follows describes an assembly for which brazing replaced staking to ensure against loosening.

Example 571. Brazing Instead of Staking To Prevent Loosening of Components in a Stop-Plate Assembly (Fig. 39)

The assembly shown at the top of Fig. 39, of which all components were of 1117 steel, functioned as a governor stop for a fuel-injection pump on a diesel engine. The threaded stud served as a means of moving the stop block back and forth, as needed, to adjust for maximum engine speed. The stop surface was opposite the side to which the pin and stud were attached. Assemblies were brazed in the position shown in Fig. 39, but they operated with the stud horizontal and the stop surface vertical. The pin served as a guide, and prevented radial movement of the stop block. All forces were compressive and against the shoulder of the stud, which meant that the assembly could have operated without fastening (beyond pressing the components together) had it not been for the vibration to which it was subjected.

Originally, the pin and stud were pressed into the block and staked. But, in several instances, the parts loosened from vibration; on one occasion, the assembly fell apart, resulting in a runaway engine.

To prevent any further accidents, the assembly was furnace brazed, using 0.020-in.-diam copper wire as filler metal, a box-type (pusher) furnace at 2050 F, and an exothermic atmosphere. The assemblies were loaded on Inconel trays for brazing. Time in the brazing chamber was about 12 min. It was possible to braze about 1500 assemblies per hour.

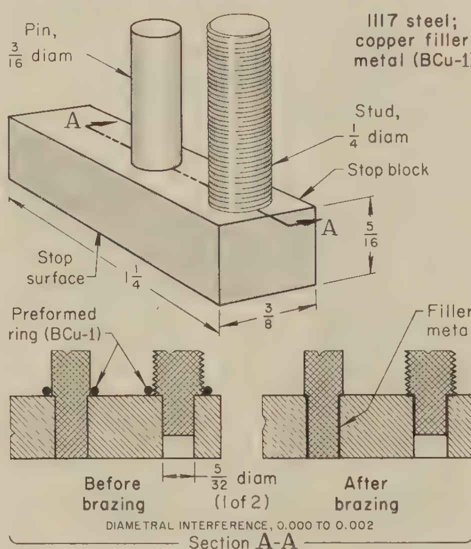


Fig. 39. Stop-plate assembly for a fuel-injection pump. Originally, the pin and stud were secured in the block by staking, but a change was made to copper brazing to ensure against loosening. (Example 571)

Substitution for Forging or Casting. Furnace brazed assemblies comprising two or more separately machined components may be more economical to fabricate than a complex forged or cast component that requires extensive machining. Cost savings result from the elimination of expensive punch and die sets (with limited life), elimination of one or more difficult machining operations, or overcoming a high rejection rate resulting from porosity and other defects in the cast product, as illustrated by the applications described in the following examples.

Example 572. Reduction in Machining Costs by Substitution of a Furnace Brazed Assembly for a Machined Forging (Fig. 40)

Originally, the tappet-shell assembly shown in Fig. 40 was finish machined from a single forging. The forging was produced in a hot upset forging machine, with the punch partly forming the contoured recess. Punch life was poor, and wear on the punch made it difficult to produce forgings that were within dimensional requirements. Even acceptable forgings required extensive machining, including a difficult and costly end-mill profiling operation on the contoured recess.

Production costs were greatly reduced by machining the shell and disk as separate components, assembling, and furnace brazing. Both components were machined from 1118 steel bar stock. The shell was machined from 1-in.-diam bar stock in an automatic bar machine by drilling the body and counterboring one end to receive the disk. After they were cut off, 25 shells were placed end-to-end, and the contoured recess was broached in a single operation. The shells were then placed side-by-side for broaching the top slot.

The disks were machined from 13/16-in.-diam bar stock by turning and by chamfering one edge. The counterbore in the shell was machined to provide a diametral interference fit of 0.001 to 0.003 in. with the disk. During assembly, a preformed ring of 0.032-in.-diam BCu-1 copper filler-metal wire was placed in the circular cavity between the chamfer on the disk and the inner wall of the shell, and the shell was forced over the disk by use of an arbor press.

The assemblies were loaded, disk side down, on 11-by-32-in. trays, 200 assemblies per tray. Each trayload of assemblies was brazed at 2050 F in an electric box furnace for 15 min, in an exothermic atmosphere. Production rate was 800 assemblies per hour per furnace.

Example 573. Substitution of a Furnace Brazed Assembly for a Casting To Eliminate Leakage (Fig. 41)

Originally, the leakoff-valve assembly shown in Fig. 41 had been produced as a single machined brass casting, but porosity of the casting resulted in leakage in service, and so the method of producing the leakoff valve was changed to assembly by furnace brazing of two pieces machined from 1113 steel bar stock.

The components of the assembly were turned and partly drilled in an automatic bar machine; the transverse hole was drilled in a drill press. The components were assembled, and filler metal in the form of a preformed ring of copper wire (BCu-1) was slipped over the inserted component and located, as shown in Fig. 41. Assemblies were then loaded on furnace trays, with the inserted component upright.

The assemblies were brazed at 2050 F in an electric box furnace, in an exothermic atmosphere. After brazing, drilling was completed and the hole in the inserted component was threaded.

APPENDIX 1

Safe Operation of Brazing Furnaces

By H. M. WEBBER*

In starting up, operating, shutting down, and maintaining brazing furnaces that contain protective atmospheres, it is important that correct procedures be followed for the safety of personnel and equipment. Safety features are available to help guard against making unfortunate mistakes, but the best safety feature of all is a well-trained operator who thoroughly understands the equipment, the nature of the gases utilized, and the importance of correct procedures. An operator who understands these fundamentals will be well equipped to understand supplementary instructions for specific types of furnace equipment,

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and will be capable of operating the equipment with safety and confidence.

Nonflammable gases will not burn in air, or explode if mixed with air in any proportions, when exposed to temperatures that can ignite flammable mixtures. Typical nonflammable gases are nitrogen, argon, helium, and carbon dioxide, and mixtures of these gases containing small percentages of flammable gases, such as hydrogen and carbon monoxide.

Lean exothermic gas is a typical mixture of nitrogen and carbon dioxide that contains low percentages of hydrogen and carbon monoxide. A maximum of 1% hydrogen and 1% carbon monoxide will be safely below the minimum amounts of hydrogen and carbon monoxide in room-temperature mixtures of lean endothermic gas with air that can explode when ignited by hot furnace components (see "Flammable Gases", below). Heated mixtures in a warm furnace can be ignited more readily, but the 1% limits mentioned above will still suffice. Mixtures that do not exceed these maximums can be considered nonflammable.

The nonflammable gases can be used freely in furnaces without hazard of explosion in all mixtures with air, with furnace heat on or off, or with pilots lighted or unlighted. Caution should be observed with carbon monoxide, however, because of its toxic effect, discussed below under "Carbon Monoxide Poisoning and Suffocation Hazards", and with gases heavier than air — namely, argon and carbon dioxide — which can flow out of furnaces and lie low to cause suffocation.

Flammable Gases. The most potent flammable gas commonly encountered in furnace atmospheres is hydrogen. Others are carbon monoxide and methane (CH_4). Flammable prepared mixtures containing hydrogen, carbon monoxide and a small amount of methane, together with percentages of nonflammable gases, include rich exothermic gas, purified rich exothermic gas, and endothermic gas. Dissociated ammonia (75% H_2, 25% N_2) is, of course, highly flammable.

When a brazing furnace chamber contains 3% or less of hydrogen and a similar amount of carbon monoxide, or more than 75% of hydrogen and carbon monoxide, it is safe from explosion if mixed with air at ignition temperatures.* However, all in-between percentages of flammable gas mixed with air can explode with considerable violence, producing pressure, heat and flames that can destroy or damage equipment and injure or kill personnel. It is most important that the furnace operator understand these basic principles, and that he take precautions to see that ignition, such as may result from turning on the heat or lighting the pilots, does not take place except under *known safe* conditions.

Test results indicate that hydrogen-air mixtures can be explosive at room temperature and can be ignited by a hot spark in a glass tube when the hydrogen content is as low as 4%, or as high

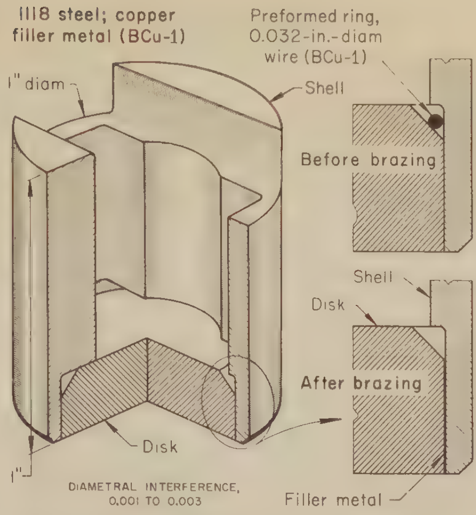


Fig. 40. Tappet shell that was produced as a two-piece brazement instead of a forging, to decrease cost of machining (Example 572)

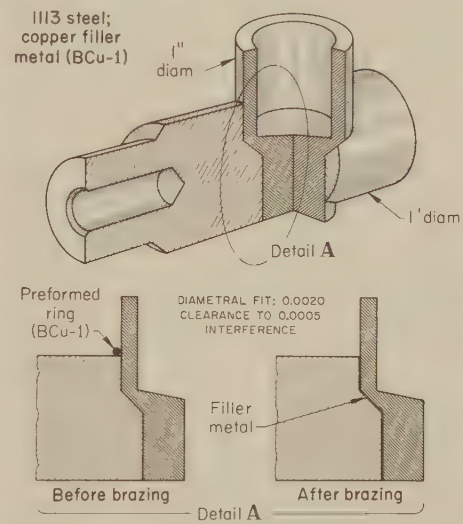


Fig. 41. Leakoff-valve assembly that was changed from a brass casting to a two-piece steel brazement, to avoid leakage due to porosity in the casting (Example 573)

as 75%, by volume. If the mixture is heated before ignition, the low limit decreases and the high limit increases as the temperature increases. Therefore, it is suggested that all concentrations of hydrogen *in excess of 2%* be considered flammable. Although the room-temperature upper flammable limit of a mixture of hydrogen in air is 75% hydrogen, the remaining 25% is air made up of 21% oxygen and 79% nitrogen, and at room temperature, a hydrogen-air mixture containing oxygen in amounts of 5% or more is explosive. At elevated temperatures, the dangerous oxygen level decreases to 3%. In mixed gases containing air, a carbon monoxide content of 12% or more by volume is explosive at room temperature; the explosive level decreases to 9% carbon monoxide at elevated temperatures.

In laboratory tests to determine explosive limits, electric hot sparks have been used as sources of ignition, as mentioned. In brazing furnaces, however, the ignition source can be a hot heating element, hot muffle, or some other component. Also, static electricity may be present where there is gas flow, which presents the possibility of an electric static discharge.

Ignition Temperatures. The minimum ignition temperature of hydrogen in air or oxygen is about 1065 F (574 C). For carbon monoxide, the ignition temperature is about 1202 F (650 C). Thus, an explosive mixture will ignite if exposed to these temperatures or to higher temperatures. If a furnace is to be purged by the burnout method, as discussed in a later section of this Appendix, these combustible gases should not be fed to the furnace until the furnace temperature is 1400 F (760 C) or above, thereby ensuring ignition of the combustible gases as they enter the air-filled furnace.

Purging is the replacement of one atmosphere in a furnace or retort with another atmosphere, in such a manner as to prevent the formation of an explosive mixture. In brazing furnace operation, at start-up, the air in the furnace or retort is replaced with a nonflammable gas, followed by a flammable protective-atmosphere gas, or the burnout method is used. At shutdown, the flammable furnace-atmosphere gas is replaced by a nonflammable gas (or the burnout method is used), followed by filling the furnace or retort with air. Purging with nonflammable gases and by the burnout method is discussed in subsequent sections of this Appendix.

Critical Periods

In operating a furnace containing a flammable protective atmosphere, there are four potentially critical periods:

1 When introducing the flammable protective-atmosphere gas into the furnace chamber
2 When opening a cold chamber filled with flammable gas
3 When removing the flammable atmosphere gas and allowing air to re-enter the furnace
4 When the flow of flammable gas to the furnace is accidentally interrupted during otherwise normal operation.

Items 1 and 3, which relate to purging, are discussed in subsequent sections of this Appendix; items 2 and 4 are considered in the next two sections.

Cold Chambers

Cold chambers (such as water-jacketed horizontal cooling chambers attached to heating chambers, and cooling bells) containing flammable atmospheres are hazardous unless adequately protected and properly operated. To ignite the flammable atmosphere gas safely as it contacts the room air, and to prevent the formation of an explosive mixture inside the chamber, placement of gas-flame pilots and flame curtains at the end doors is highly recommended. If possible, end doors should be opened a minimum height to inhibit infiltration of air. If end doors that are normally closed are constructed to be sloping rather than vertical, they will allow faster ignition of the atmosphere gas as it leaves the furnace when they are opened. Room drafts arising from open doors and windows should be kept to a minimum.

*Wilbert J. Huff, Gaseous Fuels, "Chemical Engineer's Handbook", Third Edition, McGraw Hill Book Co., 1950, p 1584, 1585, 1586.

If possible, the furnace should be situated so that the normal room drafts are crosswise to, rather than parallel with, the length of the furnace. Ventilating fans and room inlets for makeup air should be strategically located for this purpose. Baffles may have to be erected at vital points near the furnace to block normal room drafts, or to divert unexpected drafts.

Emergency Procedure When Flow of Flammable Gas Is Interrupted

Whenever flow of flammable gas to the furnace is interrupted, the operator should make an immediate attempt to re-establish flow. If this is not possible, and flow cannot be restored immediately, the furnace should be purged, by either the nonflammable-gas method or the burnout method, to ensure maximum safety. The type of furnace and the degree of flammability of the gas may affect the time delay permissible before purging, but the recommended procedure is to immediately, and automatically, start purging with nonflammable gas and to sound an alarm.

If an emergency supply of nonflammable gas is not available and the flow of flammable atmosphere gas cannot be restored promptly, the burnout method of purging should be used. For box and other straight-through furnaces, continuously burning gas pilots will supply a source of ignition. If these are not available or are not operative, portable torches should be used, or twisted newspapers or oily waste should be laid across the full width of outside door openings and lighted. Then the doors should be partly opened. The pilots, torches, newspapers or waste should be kept burning until the residual gases are burned out.

For a bell or elevator type of brazing furnace, with retorts, it is recommended that nonflammable gas be made available, and that an automatic system be provided to purge the retorts with nonflammable gas in the event of failure of flammable-gas supply, and to sound an alarm.

Leaky Gas Valves

Safety shutoff valves and manual shutoff valves in flammable-gas lines have been known to leak when closed. Such leaks can, of course, allow flammable gas to seep into the furnace chamber, muffle or retort during standby periods, when it is assumed that the furnace is free of flammable gas. Gas-valve leaks are potentially dangerous. For example, if a small leak should supply flammable gas to an air-filled furnace or cooling chamber over an extended shutdown period while the furnace is cold, an explosive mixture could develop. This mixture could be ignited when the furnace heat was turned on at start-up, prior to purging. Ignition could trigger a dangerous explosion. Several simple precautions can be taken to minimize or prevent explosions caused by leaky valves, the best of which is to provide "block-and-vent" valves. First, there should be a safety shutoff valve in the flammable-gas line, followed by a normally closed solenoid-operated (or, if preferred, safety shutoff) blocking valve. The interconnecting pipe between these valves should have joined to it a venting line running to the outdoors at a safe location, and the venting line should be equipped with a solenoid-operated vent valve that is normally open. When the two mainline valves are open, the vent valve should be closed. When the mainline valves are closed, the vent valve should be open to permit drain-off of any flammable gas that might leak through the closed safety shutoff valve.

Table 6. Nonflammable Gases Used for Furnace Purging

Gas	Specific gravity(a)
Argon	1.379
Carbon dioxide	1.527
Helium	0.137
Nitrogen	0.972
Lean burned dissociated ammonia ($99\ N_2$, $1\ H_2$)	0.963
Lean exothermic gas	1.030
Lean purified exothermic gas	0.966

(a) Specific gravity of air is 1.000.

Leaky Retorts or Muffles

Leaks in furnace retorts and muffles invariably provide their own warning signals: deterioration in the appearance and quality of the work and an appreciable increase in the dew point of the atmosphere within the retort or muffle. Nevertheless, all retorts and muffles should be pressure or vacuum tested periodically, and whenever a leak is detected, it should be repaired promptly.

When a muffle can be removed from the furnace, it can be tested more conveniently without the encumbrance of the surrounding furnace. However, many muffles are built into the furnace and are difficult to remove. Testing a built-in muffle often can be accomplished by removing the mesh belt and by sealing the extreme ends of the furnace for pressure or vacuum testing. The sealing is generally accomplished by clamping steel plates with gaskets to the entrance and exit ends of the furnace.

When it is suspected that a muffle is leaking and the furnace is in operation at high temperature, the hot chamber should be permitted to cool down to 1400 F and should then be purged with nonflammable gas or by the burnout method, as described in the sections on purging in this Appendix.

Carbon Monoxide Poisoning and Suffocation Hazards

The possibility of carbon monoxide poisoning is always present in the vicinity of a protective-atmosphere furnace or gas generator when the atmosphere gas contains carbon monoxide. Usually, the atmosphere gases coming from furnaces are satisfactorily controlled by adequate room ventilation or by exhaust systems, or by burning the escaping gases at flame curtains. However, if the ventilation or exhaust is poor, or if atmosphere gases containing carbon monoxide are not burned at furnace openings, there is a definite hazard.

Because carbon monoxide is colorless, odorless, tasteless and nonirritating, a person inhaling air contaminated with carbon monoxide receives no warning of its presence. He should, therefore, be warned of the toxic effects of carbon monoxide and be acquainted with the symptoms of its effects.

A comparatively small concentration of carbon monoxide can have a marked effect on a person. According to Bureau of Standards Technical Paper 212, safe concentrations of carbon monoxide in air are less than 0.01%. Exposure to 0.04% for about 1½ hr may produce the characteristic primary symptoms of headache, mental dullness, and physical loginess. Greater concentrations or longer exposure times may prove fatal. Accordingly, when symptoms are noted, personnel should leave the area at once and report the condition to the proper authorities. Simple and inexpensive testing equipment for detecting carbon monoxide and warning of its presence is available. If safe limits of carbon monoxide are to be established for given working environments, medical authorities should be consulted.

If personnel are to enter a furnace that has been shut down for repairs, particular care should be taken to ensure that all gases, particularly (but not exclusively) those containing carbon monoxide, are first flushed out of the furnace with air. In addition, a continuous flow of fresh air from a fan or blower should be provided to the furnace during the repair periods. For safety, some users require that atmosphere-gas supply lines be disconnected from the furnace gas-inlet lines during repair periods. This eliminates the hazard of depending on shutoff valves, which might leak.

Suffocation and death can occur from lack of oxygen, either within or outside the furnace. As gases that are heavier than air — namely, argon and carbon dioxide — flow out of the furnace, they lie near the floor and can cut off the supply of oxygen.

Purging With Nonflammable Gas

These recommendations apply to all types of furnaces with protective-atmosphere heating chambers, with or without muffles or retorts, rated at any temperature, and heated by all types of heat sources. Where practical, it is preferable to purge an air-filled furnace with nonflammable gas prior to introducing a flammable-gas atmosphere. Likewise, during shutdown, it is preferable to purge the flammable gas with nonflammable gas. This applies particularly to heated furnaces, or sections of furnaces, that are below the generally reliable gas-ignition temperature of 1400 F (760 C). Flow-rate indicators and a time clock should always be used to ensure complete nonflammable-gas purging, and a method for checking the extent of purging is often highly desirable.

When air is purged from a furnace chamber using nonflammable gas, a volume of nonflammable gas equal to about five volumes of the chamber may be needed to reduce the oxygen content to about zero per cent. For maximum safety, most operators observe the five-volume rule. Typical nonflammable gases used for purging are listed in Table 6. The extent of purging by removing air with nonflammable gas can be determined with the use of an oxygen analyzer or a specific-gravity indicator. The same specific gravity indicator can also be used to determine the extent of purging flammable gas with nonflammable gas when the furnace is being shut down.

The density of the purging gas has some bearing on the purging procedure. When a chamber is purged by replacing one gas with another, the least amount of mixing is generally desirable and permits the most rapid and economical purging. If the density of the two gases is approximately the same, as, for example, air (sp gr 1.0) and nitrogen (sp gr 0.972) or lean exothermic gas (sp gr 1.03), it will make little difference as to the manner in which the two gases are brought together, and therefore, if the air in a chamber is to be displaced by nitrogen, the nitrogen can be introduced at the top or at the bottom, whichever is more convenient, assuming that there is an opening at the opposite extremity for allowing the gases to escape.

If, however, it is desired to replace air (sp gr 1.0) with helium (sp gr 0.137), it is preferable to introduce the helium at the highest level, so that it can collect at the top and force the heavier air out at the bottom, with a minimum amount of mixing of the two gases. If the purging gas is argon (sp gr 1.379) or carbon dioxide (sp gr 1.527), the purging gas should be introduced at the bottom, so that the lighter air can escape at the top. The same principle applies when shutting down a furnace or taking a retort out of service, when it is necessary to replace the flammable gas with a nonflammable purging gas.

In some furnaces, it may be impractical to employ the density consideration, and the gases may have to be diffused with turbulence and mixed, regardless of specific gravity, in order to replace one with the other. In general, this can be done satisfactorily, but it is likely to involve more time and greater expense.

Follow-Up Purging With Flammable Gas. After purging with nonflammable gas and before starting up, the next step is to purge with flammable gas. Here, too, about five volume changes will generally ensure complete purging. Purging with flammable gas also should be measured with flow-rate indicators and a time clock, to ensure complete replacement.

Some typical flammable gases and their specific gravities are shown in Table 7. All of the flammable gases in Table 7 are lighter than the nonflammable gases in Table 6, except for helium.

When it is assumed that the chamber is completely purged with flammable gas, it is highly recommended that the composition of the effluent from the furnace be checked, using one of the methods listed in the following paragraph, to make *sure* that it is not explosive, before turning on the heat, lighting pilots, or providing a source of ignition in any other way. Such routine checks may seem to be of little value when other prescribed procedures are adhered to, but they can show up a rare mistake by the operator or a fault in the equipment and will help to prevent an explosion that might otherwise occur. For example, the furnace operator could forget to purge with nonflammable gas prior to injecting the flammable gas; the flow rate or time interval for either of the purging gases could be inadequate; or an unnoticed crack in a retort or muffle, or an open door or pipeline, could provide a source of unwanted air.

Table 7. Flammable Gases Used for Furnace Purging

Gas	Specific gravity(a)
Hydrogen	0.069
Dissociated ammonia (75 H_2, 25 N_2)	0.295
Dissociated ammonia burned with air, rich (24 H_2, 76 N_2)	0.755
Rich exothermic gas:	
Unpurified (15 H_2)	0.858
Purified (15.5 H_2)	0.825
Endothermic gas:	
Dry (38 H_2)	0.622
Wet (28 H_2)	0.798

(a) Specific gravity of air is 1.000.

Several methods are available for determining whether the flammable gas in the cold chamber is safe or explosive. A specific-gravity indicator is effective for this purpose. An oxygen analyzer of the proper type can also be used. Some oxygen analyzers operate on a combustion principle, which would supply a hazardous source of ignition to an explosive atmosphere. Safe instruments are the chemical-absorption type and the magnetic-susceptibility type of oxygen analyzers, which provide no source for ignition. An atmosphere sample can be collected in a test tube and ignited at a safe distance from the furnace. Quiet burning or a pop or whistle will indicate its nature. After it has been determined that the furnace is safely filled with flammable gas, and there is no chance for the atmosphere to explode, it is safe to turn on the heat, to light pilots, or otherwise to subject the furnace atmosphere to ignition sources.

Purging by the Burnout Method

The burnout method of purging is utilized where it is impractical to purge an air-filled furnace with nonflammable gas before a flammable-gas atmosphere is introduced during start-up, or to purge out the flammable gas with nonflammable gas during shutdown. The following procedures apply to horizontal furnaces with heating chambers rated at 1400 F or above, with attached relatively cool chambers that may or may not be heated for preheating, burn-off, purging and cooling. These procedures do not apply to furnaces with molybdenum or tungsten heating elements, because such elements are seriously damaged in an air atmosphere at 1400 F or above. Furnace types covered include box, pusher, mesh-belt conveyor, and roller-hearth conveyor.

In the burnout method of starting up, a flammable gas is injected directly into the air-filled heating chamber after the chamber has been heated to approximately 1400 F. Care must be taken not to inject the gas into adjoining air-filled cool chambers, where explosive mixtures could form. If the main heating chamber has a muffle, these instructions apply only if a gas inlet leads directly into the muffle.

Start-up safety can be ensured by having a safety shutoff valve in the flammable-gas line to the furnace interlocked with a 1400 F contact in a furnace temperature-control instrument. This arrangement ensures that only when the furnace is 1400 F or above can flammable gas be supplied to it. If the furnace temperature drops below 1400 F, the safety shutoff valve will close and stop the flammable-gas flow and sound an alarm. An auxiliary timer and solenoid valve in the atmosphere-gas line to the cooling chamber should allow flow only after adequate time has elapsed for complete burnout purging by the gas entering the heating chamber.

If the furnace operating temperature is to be below 1400 F, such as might be required for silver brazing, the foregoing procedure would need to be modified slightly. First, the furnace should be heated to 1400 F and purged as described in the preceding paragraphs. When that temperature has been reached, the auxiliary contact in the temperature-control instrument can be bypassed with a holding relay, and the temperature can be lowered safely without the contact closing the safety shutoff valve and cutting off the atmosphere-gas flow to the furnace. To shut down the furnace after use at reduced temperature, the furnace should be reheated to 1400 F and the burnout procedure followed as outlined below. Or, if the alternate nonflammable-gas procedure is preferred, shutdown can be instituted directly from the low operating temperature.

During start-up, as the flammable gas enters the brazing chamber, which has been heated to 1400 F or above, the gas burns oxygen out of the air. It continues to burn and to spread into adjoining chambers, eventually flooding the entire furnace and making it ready to operate with protective atmosphere.

During shutdown, the procedure is reversed. The flammable gas is ignited at an opened end door, and gas flow is shut off. As the gas burns, air sweeps in and the flammable constituents are entirely consumed, leaving the furnace filled with air and nonflammable products of combustion.

Procedures for Start-up and Shutdown, Using the Burnout Method

For convenience, the following lists present, in chronological sequence, the typical steps to be taken in starting up and shutting down a horizontal furnace of the box, mesh-belt, or roller-hearth type, using the burnout method. For a particular furnace, the manufac-

turer's operating instructions should be consulted and followed, since a typical procedure cannot be employed for all types and makes of equipment.

Procedure for Start-up

1 Open wide all furnace doors.
2 Make sure all inlets for flammable atmosphere gas are shut off tight, and have been so for some time. If there is any question that there has been some leakage, do not turn on the heat source or light any pilots or curtains. First blow or flow air or nonflammable gas into the furnace, taking particular care to purge high spots such as the arched roof and refractory door cavities. Vent the nonflammable gas outdoors, so that it cannot accumulate in areas where there are personnel.
3 Turn on heat and bring main heating chamber up to 1400 F (760 C), or above.
4 If there is a heated preheat or precool chamber attached, with muffle, bring it up to 1400 F also, preparatory to burning any flammable gas that might leak through pores or cracks in the muffle. If the maximum temperature rating is below 1400 F, or if there is no muffle, heating of this chamber is optional.
5 Close all purge and vent pipes.
6 Light all pilots at flame curtains, purge pipes and vent pipes.
7 If the hot chamber (or chambers) is double-ended and has an attached cool chamber (or chambers) at only one end, close the outer entrance door to the hot chamber, leave all intermediate throat-baffle doors wide open, and lower the outer exit door of the cool chamber to an opening of 2 or 3 in. For this purpose, gas-flame curtains should be adjusted to extend only slightly above hearth level to facilitate seeing the atmosphere-gas flames described in item 9 below.
8 If attached cool chambers are at both ends of the hot chamber (or chambers), leave all intermediate doors wide open and lower both outer entrance and exit doors to openings of 2 or 3 in. Adjust gas-flame curtains in accordance with item 7.
9 Start flow of flammable gas into hot (1400 F or above) main heating chamber, using a flow rate equivalent to normal consumption. Continue until atmosphere gas burns at the outer entrance and exit doors. The burning of gas at the furnace doors is an indication that all air has been burned out and that the furnace is filled with protective atmosphere.
10 Lower and raise intermediate refractory doors. Piston action in upper door cavities may create vacuum or pressure, causing air to rush in or gas to be pushed out forcefully at end openings. Slower door-operating speed will usually rectify this objectionable effect. Reduce speed of air-operated doors by closing down the small needle valves in vent lines of the pneumatic cylinders.
11 Open the outer end doors wide and adjust gas-flame curtains to full height to cover the openings completely with nearly transparent flame.
12 Close all outer end doors and intermediate doors, if so desired.
13 Open purge and vent pipes as desired. Atmosphere gas will be ignited by the pilots.
14 Bring temperature of heating chamber (or chambers) up or down to desired operating temperature.
15 As a drying-out procedure, allow time for heat to soak into refractory walls and moisture to be purged out of protective atmosphere.
16 The furnace should now be ready for operation.

Procedure for Shutdown

1 Adjust temperature of hot chamber (or chambers) to 1400 F (760 C) or above.
2 Open all interior doors wide.
3 Provide continuous, reliable ignition sources at both outer entrance and exit doors. These may be pilot lights, low-burning gas-flame curtains, or portable torches. The gas-flame curtains for this purpose should be adjusted to extend only slightly above hearth level to allow fresh air to sweep over them into the furnace after the outer end doors of the furnace are opened and the atmosphere gas is burning.
4 Partly open outer entrance and exit doors. Be sure atmosphere gas is ignited.
5 Shut off flow of flammable atmosphere gas to all inlets of hot and cool chambers. The ignited atmosphere gas will burn with insweeping air throughout the furnace, and the flame will extinguish itself in a few minutes.
6 Caution: *Make sure that all atmosphere-gas shutoff valves are closed tightly and do not leak.* Use of the block-and-vent valves previously described will ensure against leakage.
7 With the inner flame extinguished and all chambers filled with air and nonflammable products of combustion, all pilots and flame curtains may be extinguished and the heat source (or sources) shut off.
8 Leave all furnace doors open for self-venting in the event of leakage of flammable gas.
9 At this stage the furnace can be considered completely shut down.

APPENDIX 2

Application of Vacuum Furnace Brazing

Stainless steel heat-exchanger modules, the tubes and interconnecting fins of which are made by brazing together identical sections of corrugated strip in a stacked-honeycomb arrangement, are among the wide variety of assemblies fabricated from stainless steels, heat-resisting alloys, titanium, and refractory metals that are brazed in vacuum furnaces capable of developing a vacuum pressure of 10^{-7} torr and temperatures as high as 3000 F. These modules are used in the oil systems of large aircraft.

The main body, or stack, of the module is made up of sections of corrugated type 321 stainless steel strip 0.003 in. thick. Prior to brazing, the corrugated strip sections are preassembled and held in alignment by spot welds that are deposited along the fin sections separating corrugations. Nickel alloy filler metal (AMS 4778), in the form of powder, is mixed with an acrylic plastic binder and a thinner, such as acetone or xylene, and sprayed in precisely measured quantities on the backs of the sheets. The sheets are then arranged in stacks and are held in position by brackets that become part of the module assembly. When assembled, a typical module is a 12-in. cube. The modules are brazed at 1980 ± 20 F in accordance with the following procedure:

1 Eight modules are placed in the vacuum furnace.
2 A total of six thermocouples are attached to the thinnest and heaviest sections of the modules.
3 The furnace is sealed; pumpdown begins.
4 The furnace is heated; pumpdown continues to pressures of 10^{-4} to 10^{-5} torr.
5 Heating continues to 1075 F; to equalize, the furnace is held at 1075 F for 30 min.
6 Heating continues to 1675 F; to equalize, the furnace is held at 1675 F for 30 min.
7 Heating continues to brazing temperature, 1980 ± 20 F; furnace is held at this temperature for 5 min.
8 Furnace is backfilled with argon and fan-cooled to room temperature.

The total elapsed time for completion of the above cycle is 4 hr. Approximately 2000 joints are brazed on a single module.

Metals Brazed. The metals most commonly brazed in vacuum furnaces are the austenitic and martensitic stainless steels, solid-solution and age-hardenable heat-resisting alloys, titanium and titanium alloys, and refractory metals, such as columbium, tantalum and zirconium. The reasons for selecting vacuum brazing in preference to conventional furnace brazing under protective atmospheres vary considerably. For example, many of the age-hardenable heat-resisting alloys contain aluminum or titanium; these alloying elements, when heated, form refractory oxides that interfere with wetting and that cannot be reduced in reducing protective atmospheres, including dry hydrogen. Titanium, titanium alloys, columbium, tantalum and zirconium cannot be brazed in any of the protective atmospheres other than argon without suffering contamination and embrittlement, but argon does not ensure good wetting by the filler metal. Stainless steel assemblies, such as the heat-exchanger module, are brazed in vacuum partly to ensure complete purging of internal cavities. Often, brazing and heat treatment are combined in one operation.

Filler metals containing alloying elements with low boiling points or high vapor pressures are studiously avoided. Nickel-base, copper-base, gold-base, palladium-base, and a few silver-base filler metals are commonly used in vacuum furnace brazing. Metallic impurities in all these filler metals are rigorously controlled. Apart from compatibility with the base metal, filler metals are invariably selected for corrosion resistance in specific media and suitability for service at known operating temperatures. Pure copper, for example, is seldom used as a filler metal, because its upper temperature limit for continuous service is only 400 F (as compared to about 800 F for gold filler metals and about 1200 F for nickel filler metals). Many of the filler metals in common use are nonstandard, as for example, those containing 92% gold and 8% palladium; 50% gold, 25% palladium and 25% nickel; and 65% silver, 20% copper and 15% palladium.

The amount of filler metal applied to the joint area is usually carefully controlled for two reasons: (*a*) wetting action is excellent, and excess filler metal flows without hindrance to areas where it is neither needed nor wanted; and (*b*) excessive interalloying of base metal and filler metal is often harmful to joint strength.

Furnaces. Both hot wall (retort) and cold wall (radiant shield) furnaces are used in vacuum brazing; however, because of inherent advantages, cold wall furnaces are by far the more widely used. Cold wall furnaces heat faster and with greater efficiency, and are suitable for use at higher temperatures and vacuum pressures. For example, the upper operating temperature limit for a hot wall furnace is about 2200 F, as compared to about 3000 F for a cold wall furnace. At the higher operating temperatures, the ability of the retort of the hot wall furnace to resist collapse is increasingly dependent on the supporting vacuum surrounding the retort.

Other Examples of Furnace Brazing in This Volume

Metals brazed	Example
Aluminum alloy 6061	633
Copper alloy 102	634
Copper alloy 102 to molybdenum	638
Copper alloys 220 to 122; 172 to 340, 220 and 172	636
Copper alloy 757	637
Copper to fine silver	635
Gray iron	612
Gray iron to steel	613
Stainless steel, type 347	616, 617, 619
Stainless steel, types 303 and 305 to PH 15-7 Mo	618
Stainless steel, type 410	620, 621
Stainless steel, type 304 to 403	622
Stainless steel, type 304 to 17-7 PH and to copper alloy 145	623
Stainless steel, type 302 or 430	624
Stainless steel, type 347, to titanium	625
Stainless steel, types 304 and 446, to copper alloys	626

Torch Brazing of Steel

*By the ASM Committee on Brazing of Steel**

TORCH BRAZING is a brazing process in which the heat is obtained from a gas flame or flames impinging on or near the joint to be brazed. Torches used in this process may be of the hand-held type or may consist of fixed burners having one or many flames. Several types of fuel gas are available for combustion with oxygen or air. Torch brazing can be done as a completely manual, a partly mechanized, or a completely automatic process.

This article deals mainly with the torch brazing of carbon and low-alloy steels. In addition to the steels discussed here, torch brazing is used on stainless steels, aluminum alloys, copper and copper alloys, and magnesium alloys. Highly alloyed steels, heat-resisting alloys, and reactive metals are usually brazed by other methods, because they require special atmospheres or closer control of the thermal cycle, or both.

Manual torch brazing is best applied where production quantities are small, since equipment cost is low. It is also used in applications where physical size, joint configuration or other considerations make it difficult or impossible to braze by other methods. The main drawbacks are the high labor content and the relative skill needed for efficient production. Where production quantities are larger, automatic torch brazing is used, often producing brazed assemblies at the rate of 400 to 1400 per hour.

Fuel Gases. Acetylene, natural gas, propane and proprietary gas mixtures are the types of fuel gas most often used in the torch brazing of steel. Hydrogen, butane and producer (city) gas are seldom used. In manual torch brazing, pure oxygen is chiefly used as the combustion agent because of its fast heating rate. As a cheaper source of lower-grade oxygen, compressed air can also be used, if lower flame temperatures and heating rates are acceptable. Either oxygen or compressed air is used in automatic torch brazing.

The economics of gas consumption plays an important role in the selection of gases. The increased production of oxygen for steelmaking and other purposes has resulted in larger supplies and lower prices. This trend has favored the use of natural gas and propane, which require larger oxygen-to-fuel ratios than acetylene, but are themselves less costly than acetylene.

Compressed air involves only the cost of compression, and advantage can be taken of this in automatic operations, where the investment in pumping and mixing equipment can be amortized with the rest of the equipment. Another factor favoring compressed air – natural gas combustion in automatic applications is that if conveyor malfunction occurs, the workpieces will not be destroyed by overheating.

Torch Brazing Principles and Technique

The principles of torch brazing differ from those of other brazing processes only in technique. The braze bond is the same; a suitable filler metal is melted in a closely fitted joint between unmelted base-metal parts and fills the joint by capillary action.

Brazing Filler Metals. The two types of filler metal established as suitable for torch brazing of steel are the silver alloys and the copper-zinc alloys described in the section on Filler Metals starting on page 627. The silver alloys are more costly but, in general, melt at lower temperatures than the copper-zinc alloys. The tensile strength of the silver alloy filler metals is about half that of the low-carbon steels, but considerably greater strength is developed when they are used in correctly designed joints. Tensile strengths of the copper-zinc filler metals are about the same as that of low-carbon steel.

Joint Design. In torch brazing of steel, the commonly used filler metals need a joint clearance (at brazing temperature) of 0.002 to 0.005 in., for capillary flow. Where thermal expansion is significant, an allowance is made on room-temperature measurements. Lap joints designed for shear loads are preferred to butt joints designed for tensile loads. Six designs for brazing of lap joints are compared with their counterparts commonly used for welding in Fig. 31 in the article on Furnace Brazing. For maximum joint efficiency, the length of the overlap should measure at least three times the thickness of the thinnest member to be joined.

Joints are designed either for face feeding or for preplacement of filler metal. Preplacements are used in joints of large area or of a configuration difficult to penetrate by face feeding. For additional discussion of joint fit and design, see pages 607 to 610 in the article on Furnace Brazing.

Prebraze Cleaning. Filler metal will not wet and adhere to contaminated surfaces. Before torch brazing, the joint surfaces must be cleaned to remove all dirt, oil, grease, rust and scale. Prebraze cleaning is discussed on page 602 in the article on Furnace Brazing.

Fluxing. A flux is applied to the joint before heating, to promote the flow and bonding of filler metal throughout the joint to be torch brazed. Flux may be applied as a powder, paste, or liquid, or as a mixed paste of flux and filler metal. It may also be applied as a vapor, through the gas flame. The types of fluxes used are discussed in the section beginning on page 628 in this article.

In order to prevent oxidation of the joint surfaces, flux must be applied so that both surfaces to be joined are completely protected as the heating operation begins. Flux is effectively applied before assembly, especially if the joints are more than about $\frac{3}{16}$ in. deep. This is done by brushing a thin layer of paste on the cold or slightly warmed joint surfaces, or by dipping the joint in paste flux heated to about 200 F or in liquid flux. Paste or liquid flux may also be applied on the joint after assembly, if sufficient distribution can be obtained as heating begins.

The latter method is frequently used in automatic torch brazing; the dependence on joint design of fluxing before or after assembly can be seen by comparing Examples 580 and 581.

Flux is often applied on the area around the joint to minimize discoloration and scaling of the workpiece surface. Although this increases flux cost, postbraze cleaning time may be reduced or eliminated. When flux is used for this purpose, it should be applied sparingly to the entire surface that normally would oxidize on heating.

Flux inclusions can be caused by the application of too much flux, by too loose a joint fit, or by overheating the workpiece. When recognized in time, these conditions often can be remedied by moving one member in relation to the other during brazing, before the filler metal solidifies. The movement will aid the filler metal in displacing the flux and in penetrating the joint area.

The filler metal also should be protected by flux. Preformed filler metal can be dipped in flux or flux can be brushed onto it. Either face-fed rod, wire or strip can be brushed with flux, or the heated end can be dipped occasionally into dry flux powder. Filler-metal powder is either dusted on wet flux or mixed with it (see the section on Filler Metals in this article).

It is important that the flux be heated to its active state and that it flow over all joint surfaces before the filler metal starts to flow. Because some oxide forms during heating, a true braze bond will not occur on surfaces that have not been fluxed, even though the joint may appear to be adequately brazed. Usually, the filler metal flows around areas not protected by flux, resulting in voids.

Heating. Brazing should be done away from drafts, to avoid uneven heating and cooling. Torches adjusted for a slightly reducing or a neutral flame are used in bringing steel parts to brazing temperature. To prevent overheating and melting of the base metal, the torch tip is held away from the surface of the work so that the inner cone of the flame does not ap-

*For committee list, see page 593. About half of the examples presented in this article were contributed by members of other Metals Handbook welding and brazing committees.

proach too closely. Heating is accomplished by the outer flame envelope. In manual torch brazing, the torch should be kept in motion to avoid localized overheating. The flame should be applied so that both members of the joint are brought to uniform brazing temperature, as follows:

1 With joint members of unequal mass, heat the more massive member first, until flux melting indicates that brazing temperature has been reached.
2 Heat the less massive member next, until it reaches brazing temperature.
3 Heat the joint last, being careful not to overheat. If preplaced, the filler metal should flow all around the joint, appearing at the joint edges, and the flame should be removed. If face fed, the filler metal should be placed on the joint before or behind the point where the flame strikes the part.
4 Avoid applying the torch heat directly on the filler metal, if possible.

In some applications, a massive member may receive all of the heating, the less massive part being heated entirely by conduction. When joining steel to another metal, the metal having the higher thermal conductivity is treated like a more massive member.

When the fit between an inner and an outer member of a joint is not as tight as desirable for brazing, the flame is applied first to the inner member, where it emerges from the outer member, in order to expand the inner member and tighten the fit. Heating then is concentrated on the outer, or more massive, member, and further heating of the inner member is mainly by conduction. Conduction will be poor if the fit is not tightened by first heating as described.

Heating should continue until the workpieces are slightly hotter than the flow temperature of the filler metal. Overheating should be avoided; excess heat will break down the flux and interfere with its action.

Brazing fluxes melt at somewhat lower temperatures than the filler metals with which they are used. Their melting serves as an indication that brazing temperature is being reached. When flux is heated, the water content first boils off leaving a powdery deposit. Upon further heating, the flux melts as a clear, thin liquid, which flows through the joint and actively protects the surfaces from oxidation. If the rules enumerated above have been followed, the joint will be at brazing temperature, and the filler metal (if face fed) will melt and very quickly flow into the joint, after contact. If the filler metal does not melt and flow after contact with the base metal, the joint is not at brazing temperature and heating must be continued.

The braze cannot be made by melting the filler metal in the flame before the joint is at brazing temperature, because capillary flow will not occur. Instead, the filler metal will accumulate on the surface. Continued heating of the filler metal, in an attempt to induce flow, may alter the alloy composition. This improper procedure is one of the most frequent causes of poor brazing results. Furthermore, melting the filler metal in the flame may be hazardous to health because toxic fumes may be generated. The heat in the workpiece should always be used to melt the filler metal.

Feeding Filler Metal. The filler metals used in torch brazing of steel are chiefly of two types: silver alloys and copper-zinc alloys. Their characteristics are discussed in the sections on Filler Metals in this article. The filler metals are usually available in several of the following forms: rod and wire of various diameters, strip (shim stock) of various thicknesses, and powder.

The quantity of filler metal required per joint depends on the volume of the joint space to be filled plus the volume of the desired fillets. Usually the joint is slightly overfilled to allow for filler-metal shrinkage. In manual face feeding with rod or wire, the size of the filler metal used should be large enough to avoid interruption of brazing to start a new length. For thin materials, the diameter of the rod or wire should be comparable, if possible, to the thickness of the thinner joint member, since thicker filler metal would melt too slowly.

Automatic face feeding of wire and powdered filler metals is described in the section on Equipment for Automatic Torch Brazing in this article; the preplacement of wire, strip and powder is discussed in the section on Filler Metals.

Quality Control and Inspection. Joint quality can be controlled by carefully checking the adequacy of each of the procedural steps involved. Inadequate cleaning, improper joint clearance, underheating and overheating are common sources of difficulty. Defects that are likely to recur are usually in the form of voids due to: (*a*) unreduced oxide or foreign matter that prevents wetting of the joint surface, (*b*) gas pockets resulting from gas evolution or vaporization of lower-melting constituents of the filler metal, (*c*) entrapped flux, (*d*) incomplete filler-metal flow, and (*e*) too short a heating time.

Small and widely distributed voids seldom affect the serviceability of the part adversely. Most inspection standards require no more than 80% coverage between faying surfaces, as revealed by peel testing or radiography.

Visual inspection is frequently used: joints are accepted if a continuous fillet is formed all around the joint, especially on the side opposite to that of filler-metal placement or feeding.

Pressure tests and radiographic examination are used to reveal defects nondestructively. In addition, destructive testing can be used both to set up the original procedure and, on a sampling basis, to check whether the procedure is under control. One form of destructive test is the peel testing of lap joints, frequently used in resistance spot welding. To make this test, one member of the joint is held in a vise while the joint is opened with a chisel, and the other member is then peeled or twisted away to reveal the condition of the bonded area.

Brazing vs Braze Welding. One of the joining methods often confused with torch brazing is the operation known as braze welding. The equipment and certain of the filler metals used in this type of joining may be the same as those used in manual torch brazing. In some applications, even the torch and filler-metal manipulations may appear the same. In general, the two joining methods differ considerably. Some of the characteristics of braze welding are discussed in the article on Oxyacetylene Braze Welding starting on page 579 of this volume.

Equipment for Manual Torch Brazing

Manual torch brazing equipment is the same as, or very similar to, the equipment used for manual gas welding. A description of the design and use of this equipment, consisting of a gas supply, regulators, hoses and a gas torch is given on page 566 in the article on Gas Welding. Although most of the equipment described in that article can be used for torch brazing, tip selection and the technique of applying the flame to the workpieces differ. The safety precautions stressed in that article apply with equal emphasis to torch brazing.

Since the high heat intensity of the oxyacetylene flame, which is usually necessary for gas welding of steel, is not necessary for brazing, other gases such as natural gas, propane and various proprietary gases may be used in combination with oxygen or, where less heat can be tolerated, with air.

The high heat of oxyacetylene flames is often an advantage in reducing labor costs by shortening brazing time. Because of its relatively high cost, oxyacetylene heating is sometimes combined with air-propane or air – natural gas heating. For instance, in production brazing of massive steel assemblies, air-propane (or air – natural gas) is used to raise workpiece temperature to about 900 F before torch brazing with an oxyacetylene flame.

The particular oxy-fuel gas combination will determine the type of gas-supply equipment and regulator design, and also may affect the size of the hoses used and the design of the torch components. The sizes of the torch components, hoses, regulators and gas-supply system also must be appropriate to the general range of heating capacity required.

Equipment for manual torch brazing varies in cost from about $100 to $500, and usually includes attachments for general welding and cutting operations. When fuel gas in cylinders is used, manual equipment is usually portable; otherwise, torch mobility is limited by proximity of the fuel gas to the work. Accessories may include heating torches and tips, gas savers, flashback arresters and gas-fluxing equipment.

Manual torch brazing is usually done on a work table covered with fire-resistant cement board overlaid with refractory brick. A supply of these bricks should be available. They can be used to aid in the positioning of workpieces, and to reflect torch heat on the part being brazed. Reflected heat can also be used to preheat parts waiting to be brazed.

Asbestos screens and heat shields are used for protecting nonbrazing personnel and surrounding equipment from the heat of the torches, and for con-

serving torch heat that might otherwise be dissipated. Such screens also protect the assemblies from drafts.

All torch brazing, whether manual, mechanized or automatic, requires adequate ventilation in accordance with ANSI Standard Z49.1, *Safety in Welding and Cutting*, especially Section 7.4, *Work in Confined Spaces*, and Section 8, *Health Protection and Ventilation*. The sources of the most harmful fumes are the cadmium-bearing filler metals and the fluorine-containing fluxes. Ventilation must be provided in the manner, and to the extent, prescribed in the standard cited above. The level of the contaminant must not exceed established threshold limit values. The filler metals that contain cadmium are identified in the section on Filler Metals (see Table 1 on page 627), and the fluxes that contain fluorine compounds are discussed in the section on Fluxes, page 628, in this article.

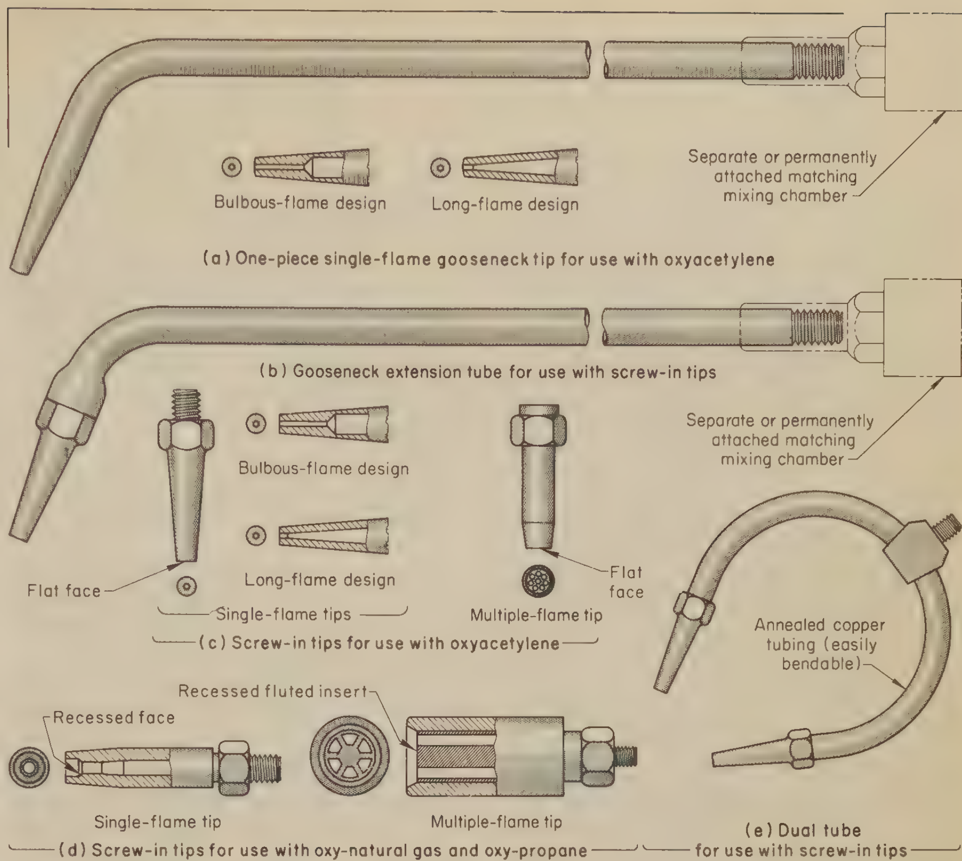
Major sources of safety rules and recommendations are listed in the section on Safety on page 578 in the article on Gas Welding.

Manual brazing torches designed for oxy-fuel gas consumption have three principal components: (*a*) the torch body, which serves as the handle and is equipped with needle valves to control the flow of oxygen and fuel gas; (*b*) a mixing head; and (*c*) a set of torch tips, which may be supplied with or without extension tubes. Essential details of these parts are shown in Fig. 3 and 4 in the article on Gas Welding (see pages 567 and 569).

Mixing-chamber design is of two basic types: equal-pressure and injector. Equal-pressure mixing chambers (also called medium-pressure and positive-pressure mixers) are used chiefly with acetylene, which can be supplied at pressures of about 1 to 15 psi; this type of mixing chamber cannot be used with fuel gas supplied at a pressure less than about 1 psi. (An equal-pressure mixing chamber is illustrated in Fig. 3 on page 567.)

Injector mixing chambers (see Fig. 4 on page 569) are used with fuel gases that are supplied at pressures less than about 1 psi or that require large quantities of oxygen. Injector mixing chambers, however, can also be used with higher-pressure fuel gases by throttling the fuel gas and oxygen by means of the torch inlet control valves. Individual adjustment is necessary for each tip size.

Because oxygen is readily available at high pressure, the injector mixing chamber is able to make use of the venturi principle by which a high-velocity jet of oxygen is made to draw or aspirate a low-pressure fuel gas. Injector mixing chambers are essential to the use of low-pressure generator acetylene and natural gas, which are often supplied at a pressure of about 1 psi or less. When using propane and certain proprietary gases that can be supplied at higher pressures, the injector mixing chamber is a convenient means of obtaining the higher oxygen-to-fuel gas ratios required. In torch brazing, volumetric oxygen-to-fuel gas ratios are approximately 1 to 1 for acetylene, about 2 to 1 for natural gas and about 4.5 to 1 for propane.



(a) Typical one-piece tip and tube extension commonly used for oxyacetylene brazing and welding. (b) Typical two-piece tip and tube assembly that permits quick replacement of tips. (c) and (d) Basic types of oxyacetylene, oxy-natural gas and oxy-propane screw-in tips. (e) Typical dual tip holder. All of the tip designs shown are available in a range of sizes, styles and capacities, and are used with complementary torch systems and gas settings.

Fig. 1. Tip designs used in manual torch brazing

The heating capacity of a torch is determined by the fuel-gas consumption rate, which in turn depends on the size of the tip orifice and the mixing chamber. The larger the diameter of the orifice, the greater the gas flow required to produce a proper flame and the greater the heating capacity. A given size of mixing chamber can usually supply the proper gas flow for a specific range of tip sizes. Selection of a tip size outside this range necessitates replacement of the mixing chamber with one of the appropriate size. The interchangeability of mixing chambers and of tips (including tip tube extensions and adapters) is limited and is prescribed by the manufacturer of the torch.

Torch tips for manual brazing differ according to the kind of fuel gas used, the tip-orifice diameter (heating capacity), and the style. Tips used with acetylene are usually faced off square across the orifice. Tips used with natural gas and propane are recessed or cupped at the orifice; otherwise, the lower flame-propagation rates of these gases might allow the flame to be blown away by the gas jet. In general, tips of both types are available in a range of orifice diameters designated by manufacturers' code numbers, on the basis of which recommended gas settings are supplied. Also available are multiple-flame tips that provide a broader flame coverage, useful in speeding the brazing operation. Fig. 1 shows several tip designs used in manual torch brazing.

Accessories. Heating torches that make use of multiple-flame tips of the type shown in Fig. 1 (c and d) are used for brazing with the lower-melting silver alloy filler metals. Because the flames are broader, heat transfer is more diffuse than with single-flame tips. These torches are frequently used in soldering, are less desirable for brazing with copper-alloy filler metals, and are not generally used for braze welding because of the time needed to reach operating temperatures. Torches equipped with multiple-flame tips are usually of a heavy-duty type and require larger-capacity mixers than those used with single-flame tips to handle higher gas flows. They may need larger gas-supply capacity.

Gas savers are used at brazing stations to conserve gas between brazing operations. The hoses are connected to dual valves actuated by a lever that also serves as a torch rest. In one type, the torch rest shuts off the gas completely, but an adjacent pilot flame permits instant re-ignition at the previous setting when the torch is lifted. Another type reduces the flame to a small size, which reverts to its former size when lifted from the rest.

Flashback arresters are used to prevent combustion or explosion from taking place in the hose if the flame, as a result of some malfunction, should burn back through the mixer and torch

handle. If not promptly stopped, flashbacks can result in injury to personnel and damage to equipment and property. The use and installation of flashback arresters are covered in ANSI Standard Z49.1.

The two principal types of flashback arrester are the mechanical check valve and the water-seal, or hydraulic back-pressure, valve. Check valves for oxygen and fuel gases supplied at about 1 psi or more consist of small threaded fittings that are inserted between the torch and the hoses to check back flow. They may also be installed between the hoses and the regulators or line gages. When used alone, check valves are not considered thoroughly reliable as flashback arresters, since flashbacks have been known to progress through them. Some check valves are capable of checking back pressures of less than 1 psi but tend to hinder very low inlet pressures.

Where large low-pressure volumes of acetylene or natural gas are distributed by pipeline, hydraulic arresters are used. Consisting of a tank partly filled with water, with an inlet pipe extending below water level and an outlet pipe terminating in the space above, these devices effectively stop the flashback. They are often used together with mechanical check valves. Utility companies often require such installations where they supply natural gas for use with oxygen. Flashback arresters are also used at the outlets of acetylene generators.

A third type of arrester consists of a closed cylinder of stainless steel wire mesh and operates on the principle of the Davy safety lamp. Installation is similar to that of the check valve.

Gas-fluxing equipment consists chiefly of a tank of liquid flux through which the fuel gas is bubbled to entrain the flux. This device is described in column 2, page 629 (see also Fig. 11).

Miscellaneous standard equipment includes: (*a*) tip cleaners, which are necessary for defouling tips, to maintain proper flame shape and to prevent tip overheating (one of the causes of backfires and flashbacks); (*b*) goggles, which are needed for eye protection; and (*c*) a set of wrenches, for proper tightening of tip, mixing-chamber hose and other connections.

Fixtures for Manual Torch Brazing

Holding devices include vises, clamps, pliers, tongs and special fixtures. Sometimes a simple holding fixture can be made to support a number of small assemblies. Ordinarily, it is preferable to make the assembly self-jigging, if possible. Where a fixture must be used, it should be constructed so that it will not interfere with the torch flame, the application of filler metal, or the operator's view. The fixture should be as light in weight as is practical, and should contact the assembly only where necessary.

Where a low heat sink is desired, point or line contact is preferable to contact over an area of surface. Ceramic points or contacts are available to minimize heat loss to fixtures.

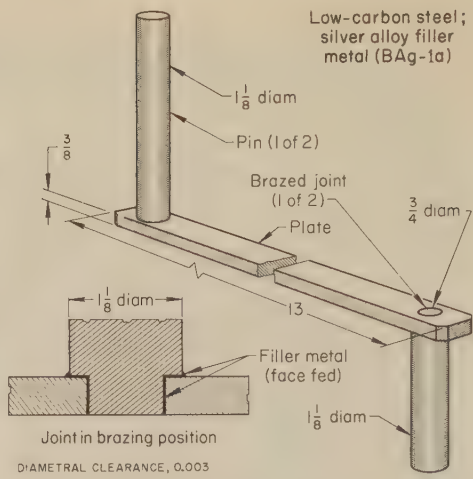


Fig. 2. Pin-and-plate assembly for which torch brazing was preferred because no fixture was needed (Example 574)

Conversely, where heat-sensitive components must be protected, larger surface contact and a conductive material, such as copper, can be used.

Asbestos shielding can be used to divert the heating effect of a torch and to protect a particular area. Shielding is used for this purpose when silver brazing small wires to avoid damage to insulation close to the joint.

The effect of thermal expansion of fixtures on joint clearance must also be considered, since the clearance must be effective at brazing temperature. In torch brazing, excessive heating of the fixture can usually be avoided and should be avoided, especially where complicated assemblies or high temperatures are involved. If parts are tightly clamped and rigid fixtures are overheated, the effect of expansion and contraction can result in overstressing of the joint and distortion of the part.

In the four examples that follow, simplicity of fixturing was one of the chief reasons for selecting torch brazing. In the first of these examples, no fixture was needed.

Example 574. Use of Torch Brazing To Eliminate the Need for a Fixture (Fig. 2)

Because the pins to be brazed were in opposite sides of the plate in the assembly shown in Fig. 2, some type of fixture would have been needed for almost any type of brazing except torch brazing. With torch brazing, one pin was brazed in place, the assembly was turned over and placed with that pin overhanging the edge of the worktable, and the other pin was brazed. The worktable was fire-resistant.

The pieces to be brazed (low-carbon steel) were cleaned in an alkaline solution, rinsed, and dried immediately before brazing. The ¾-in.-diam tenons and holes were fitted to close (0.003-in.) diametral clearance. The flux was a type 3A (see Table 2) containing an alkali borate-fluoride compound which first melted at 600 to 700 F and then became active at 1050 to 1100 F. The filler metal was silver alloy BAg-1a (see Table 1). Furnace or induction brazing was not practical because production lots were small and did not warrant the cost of a fixture.

Example 575. Use of Torch Brazing To Simplify Fixturing of a Complicated Assembly (Fig. 3)

An important reason for selecting torch brazing for assembling an air-inlet screen for a gas turbine was the simple fixture that could be used for holding the numerous parts in position. This fixture is shown in Fig. 3. All of the parts to be assembled — frame members, trunnion, and ribs — were made of 1020 steel. Before brazing, they were cleaned in a hot alkaline solution, rinsed, acid pickled, hot rinsed, and dried. The clean parts were then assembled in the fixture. Each joint was manually fluxed and torch brazed, using filler metal in wire form. After brazing, flux residue was removed by immersing the assembly in boiling water, the joints were visually inspected, and the fabricated screen was cadmium plated.

Brazing filler metal was silver alloy BAg-1a, which was well suited to torch brazing at a relatively low temperature (about 1200 F). Flux was type 3A in paste form.

Example 576. Use of Torch Brazing To Simplify Fixtures for a Tube-and-Flange Assembly (Fig. 4)

Close tolerances had to be maintained in assembling a bent tube to a support flange, as shown in Fig. 4. There was no seat in the flange to hold the 0.120/0.130-in. positioning dimension, and there were no locating features to keep the centerline of the tube and the centerline of the flange aligned within 0.010 in., as specified.

A fixture had to be built that would hold these and other dimensions while the assembly was being brazed. Because of the configuration of the part, the fixture had to be relatively large in comparison with the size of the joint to be brazed. It was considered impractical to build a number of duplicate fixtures for furnace brazing that would hold these assemblies within tolerances. A single fixture was built for manual torch brazing, as shown in Fig. 4.

Material of both tube and flange was cold drawn, low-carbon steel. The tube was 0.250-in.-OD seamless tube with a 0.035-in. wall. Diametral clearance between tube and

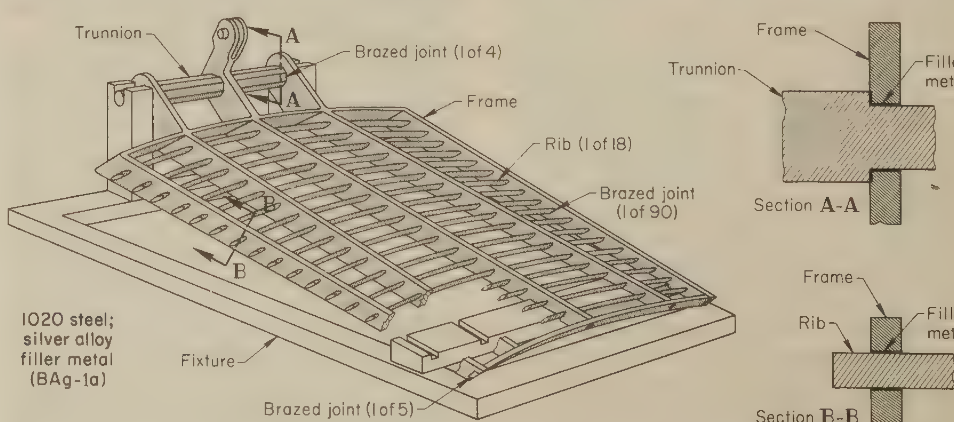


Fig. 3. Fixture for torch brazing gas turbine air-inlet screen, the assembled screen, and location of brazed joints (Example 575)

flange varied from 0.002 to 0.013 in. The parts were vapor degreased before application of a type 3A paste flux. After fixturing, the parts were brazed using a face-fed BAg-1a wire, 0.031 in. in diameter. After brazing, the assemblies were cleaned for nickel plating. Production rate was 30 pieces per hour.

Arc welding was rejected as a joining method because of possible burn-through and poor appearance. Soldering was not used because the joints would not have been strong enough.

Example 577. Use of Torch Brazing and a Simple Fixture To Meet Airtightness and Dimensional Requirements of a Tubing Assembly (Fig. 5)

The low-carbon steel tube assembly shown in Fig. 5 was manufactured in quantities of about 15,000 units annually. It was essential that the two short pieces of tubing be parallel within ±0.005 in.; that the cross-sectional area on the inside of the long tube not be decreased by more than 25% by excess filler metal; that all joints be airtight (withstand 10 psi minimum); and that a 0.170-in.-diam gage plug fit freely through the short tubes into the long tube after brazing.

The brazing fixture consisted of a V-grooved bar for the long tube with two V-grooved bars at 90° for the short tubes, two locating plugs that were inserted through the short tubes into the holes in the long tube, and toggle clamps to hold the assembly in alignment. The locating plugs were removed after the parts were clamped in place.

Joint preparation consisted of (a) drilling two holes, 0.188 ± 0.002 in. in diameter, in the long tube, (b) milling the mating ends of the short tubes to fit saddlewise over the holes in the long tube (Fig. 5) and (c) degreasing the parts in a water-soluble cleaner, and rinsing in cold water and then in hot water to speed drying. The joints were brushed with a paste flux that corresponded to an AWS type 4, and which proved to be an acceptable alternate to type 3A in this application.

Joint clearances, after fixturing, varied from 0.0005 to 0.003 in. The joints were heated by manually passing the neutral flame of the torch around the joint to heat the area to the brazing temperature, which was approximately 1200 F. The wire of BAg-1 silver alloy filler metal was then face fed at the top surface of the joint, with the assembly positioned as shown in Fig. 5 (Section A-A), and flowed around to complete the joint.

Further details are given in the table accompanying Fig. 5.

Equipment for Machine Torch Brazing

Various mechanical devices are used to perform repetitive torch brazing operations. Machines have been built for fixturing, fluxing, heating, face feeding of filler metal, forced cooling, hardening and other operations. Flowmeters and manometers are often used to monitor and control gas ratios where large gas volumes are involved. However, it is not always possible or desirable to mechanize all torch brazing operations. Workpiece configuration, joint design and accessibility, or other factors will determine whether some operations are done best by hand or by machine, even though large production quantities are involved. Machine torch brazing is the term used for operations that are partly manual, partly mechanical.

In principle, motion can be imparted to the workpiece or to the brazing equipment, or both. Usually, though, the workpiece, at a certain stage of the operation, is moved past one or more stations where a brazing function is performed manually or by machine. The two most frequently used means of movement are the conveyor belt and the turntable. Brazing operations can be set up for either mode of travel.

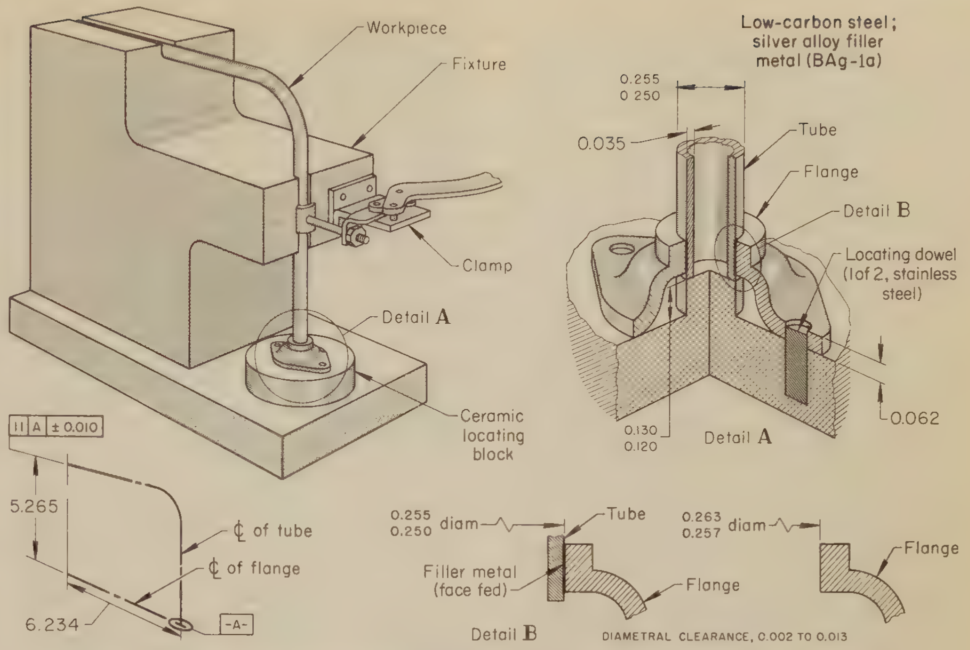


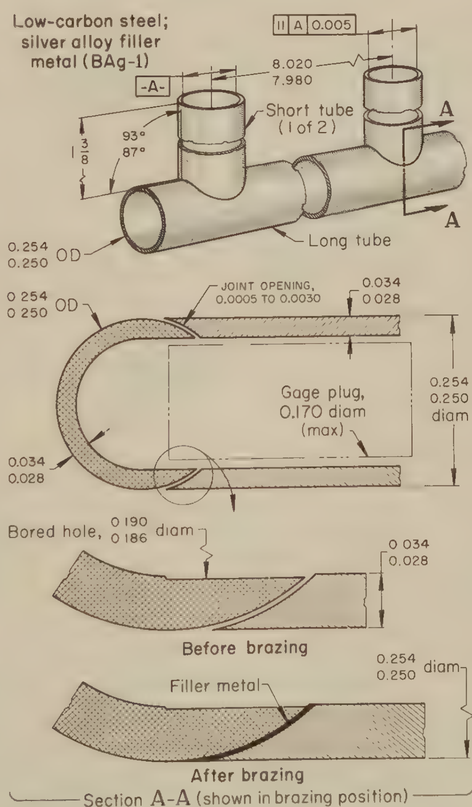
Fig. 4. Tube-and-flange assembly, showing fixture used for manual torch brazing (Example 576)

Heating is the operation most often mechanized, since it is relatively simple to move workpieces past fixed torches or burners with controlled timing. Manual operations may include fluxing, filler-metal preplacement and fit-up.

Conveyor belts are often used to carry the workpieces under a series of fixed burners and then through an air blast or water jet for cooling. In this type of setup, joint assembly, fluxing, and filler-metal addition are usually done manually before the part is placed on the conveyor.

For instance, in fabricating air-conditioner cooling coils (in this case, the base metal was copper) 18 return bends had to be brazed to the flared, open ends of the U-tubes, which had been fitted with cooling fins. The return bends were cut from tubing, formed and mechanically fitted with a preform of filler-metal wire. They were then manually fitted into the U-tubes and the assembly was loaded on hangers on a continuous conveyor belt.

On the conveyor, the assembly first was purged with natural gas flowing from a small tube inserted in one end. The assembly was then carried under two sets of compressed air – natural gas, radiant-type burners, the first set for initial heating, and the second for melting and completing the flow of filler metal. Flux was applied by gas fluxing through the burners. In addition to the conveyor system, this setup incorporated a combustion-control pumping and metering machine capable of supplying several thousand cubic feet of proportionately mixed gas per hour. Gas-fluxing equipment (see "Gas Fluxing", page 629), and a calcium chloride drying tank, were installed as part of the gas supply system. No difficulty was experienced in timing the manual operations and the conveyor speed to machine-torch braze approximately 180 air-conditioner cooling assemblies per hour.



Torch type	Oxyacetylene
Flame type	Neutral
Tip-orifice diameter	0.0380 in.
Filler metal	0.031-in. wire, BAg-1
Flux	AWS type 4
Production rate	30 assemblies (60 joints) per hour

Fig. 5. Tubing assembly that met airtightness requirements and close dimensional tolerances after brazing (Example 577)

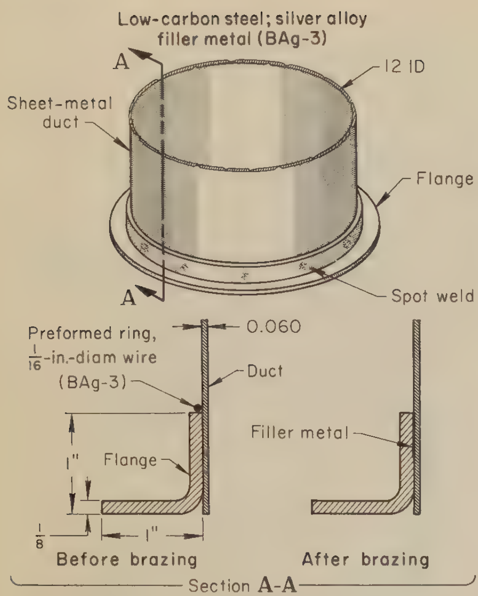


Fig. 6. Air duct on which a flange was sealed by brazing in a turntable setup (Example 578)

Turntables provide a means for any degree of automation. A circular table is fitted with a series of duplicate holding fixtures equally spaced on the rim. The number of fixtures equals the number of operating stations that are located in fixed positions around the outside of the table. At any station, the operation may be manual, partly manual and partly mechanical, or completely mechanical; the choice is determined by the nature of the workpiece. For instance, devices are built to face feed liquid, paste or powder flux at one station and wire filler metal at another, or an applicator can be used to face feed a paste mixture of powder filler metal and flux.

The joint design of the workpiece must be amenable to face feeding from one or more fixed-point sources. Even if the joint area is not so large or so inaccessible as to require prefluxing or filler-metal preplacement, there must be at least a small area on the joint where the filler metal can rest momentarily. Complex joint configurations usually necessitate hand feeding.

Heating from fixed stations presents few difficulties, because single or multiple burners can be mounted at one or more stations and connected to a common gas supply. In the more complicated torch brazing machines, the dwell time at each station is determined by the time taken for the filler-metal application; the total heating time is obtained by adding the number of heating stations needed to complete the particular thermal cycle. Air-cooling and water-cooling stations are added to obtain desired cooling rates. In some installations, turntable indexing and rotation are controlled by electronic timers.

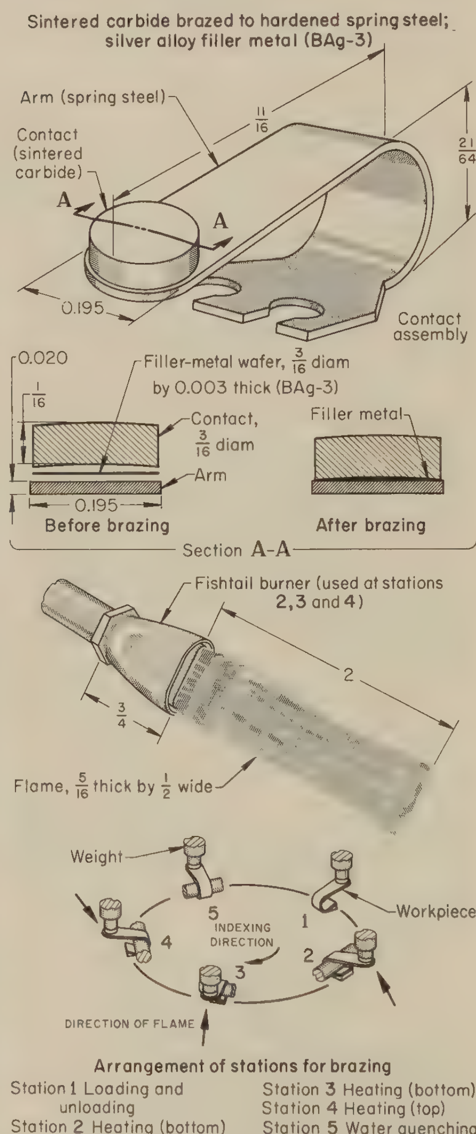
The three examples that follow describe applications in which simple turntables were used to rotate the assemblies past several heating burners to achieve required production rates at relatively low capital investment. In each application, assembly and fluxing were done manually.

Example 578. Use of a Turntable To Mechanize Heating of a Joint (Fig. 6)

Sheet-metal ducts of a closed-air system were joined by bolting companion angle-iron rings that had been cold formed and welded, and then resistance spot welded to the ducts, as shown in Fig. 6. A low-cost method was needed to seal the space between the 1-by-1-by-⅛-in. steel angle rings and the 16-gage (0.060-in.) cold rolled steel ducts. The following simple brazing operation fulfilled the requirement.

A brazing machine consisting of a turntable and six propane burners mounted around a third of its periphery was constructed at a cost of $250. Only the tips of the burners were newly purchased; they were mounted on the supply pipes.

Brazing flux (type 3A) was applied to the joint and a preformed ring of 1/16-in.-diam, BAg-3 silver alloy brazing wire was positioned as shown in Fig. 6.



Fuel system .....Premixed natural gas and air piped to each burner; 4 in. water column pressure at burner
Burner type ......Fishtail; flame 5/16 in. thick, ½ in. wide, 2 in. long; 1280 Btu per hour
Filler metal ....0.003-in.-thick by 3/16-in.-diam, BAg-3
Flux ....AWS type 3A
Production rate ....300 assemblies per hour

Fig. 7. Contact assembly that was brazed and quenched in a turntable setup (Example 579)

The assembly was then placed on the turntable and rotated past the burners, with the flames turned low, to dry out the flux. When the joint was dry, the burners were turned up to activate the flux and melt the filler metal. Sufficient flow was obtained to seal the joint.

Torch brazing was the most economical of the brazing methods that could have been used. Resistance heaters, instead of gas burners, were briefly considered, but the cost of tooling would have been about $2500. Induction brazing equipment would have cost about $20,000, and furnace brazing equipment would have cost about $25,000. The small quantity of assemblies required could not justify these costs.

Example 579. Mechanized Heating and Cooling of a Joint on a Five-Station Turntable (Fig. 7)

The contact assembly shown in Fig. 7, which consisted of a spring steel arm and a sintered carbide contact, was brazed on a turntable using burners supplied with premixed air – natural gas. Fluxing and loading were done by hand; the remaining steps were automatic, including the cooling operation. The production rate was 300 assemblies per hour, and the normal manufacturing lot was 100,000 assemblies.

The spring steel arm was supplied in the hardened condition and with a bright finish. It was vapor degreased before assembly. The parts were held by tweezers and dipped in AWS type 3A liquid flux and loaded on the turntable with a wafer of BAg-3 silver alloy filler metal, 3/16 in. in diameter (the diameter of the carbide tip) and 0.003 in. thick, between them. A weight on the top of the carbide tip held the parts in position during brazing.

Three fishtail burners, with the flat "tail" in the horizontal position, were used to heat the assemblies. Burners at stations 2 and 3 heated the assembly on the underside of the joint and the burner at station 4 applied heat to the joint on the top side to melt and flow the filler metal. Water-spray cooling followed at station 5. The hardness of the arm was not changed so as to affect its function as a spring.

Example 580. Machine Torch Brazing of a Printing-Machine Part on an Eight-Station Turntable (Fig. 8)

Magnet armatures, of the type shown in Fig. 8, were used as the striking members of a printing machine. The 0.040-in.-thick striker blade was made of high-carbon (0.65 to 0.85% C) spring steel so that the outer end, which engaged a linkage at 250 times a minute, could be locally hardened to resist wear. A brazed joint was required between the blade and the 5/32-in.-thick armature, made of 2½% silicon steel.

Conventional furnace brazing with copper filler metal was not suitable for this operation because (*a*) the slotted joint design did not lend itself to the tight fit required for copper brazing, (*b*) the high brazing temperature (2050 F) would coarsen the grain structure of the high-carbon steel blade, and (*c*) the furnace atmosphere needed to prevent decarburization of the blade was expensive.

Brazing the assemblies on a turntable using a silver alloy filler metal and either induction or flame heating would provide the desired production rate, while avoiding the objections to furnace brazing. Machine torch brazing was selected because the capital investment was lower and a metal fixture, cooled by circulating water, could be used to maintain the close dimensional tolerances required over long production runs. A timer-controlled eight-station brazing turntable was built (Fig. 8) to perform all operations except fluxing, assembling and loading, which were done manually. The burners were supplied with low-cost air – natural gas for heating.

The operating sequence was as follows:

Station 1. The operator dipped the joint end of a blade in type 3B paste flux, assembled it with an armature and loaded the assembly in the fixture.

Stations 2, 3 and 4. The joint was preheated by rotating it past burners clamped to brackets, one at each of the three stations.

Station 5. A fourth burner brought the joint to the melting temperature of the BAg-1 filler-metal wire, which was automatically face fed to the joint. A microswitch probe detected the assembly and caused the wire feeder to slide into position, face-feed 1 in. of 0.032-in.-diam wire (which melted on the joint), and retract.

Station 6. Filler metal was brought to brazing temperature by a fifth burner and flowed through the joint.

Station 7. The assembly and fixture were cooled by an air blast.

Station 8. A stationary trip pin unclamped the fixture, releasing the assembly, which was then ejected by an air-actuated plunger. The fixture was cooled by a water spray.

Production rate averaged 230 assemblies per hour. After brazing, the striker ends of the blades were hardened in a separate operation. Induction heating was used for this operation because it provided closer control over the dimension being hardened and allowed an oil quench.

Equipment for Automatic Torch Brazing

Automatic torch brazing equipment eliminates the human element from the brazing operation, except for loading and unloading of the machine. The advantages are: (*a*) high production rate, (*b*) uniform joint quality and (*c*) economy in the use of gases, flux and filler metal. Automatic torch brazing is applicable to a wide variety of small parts. Large, extended or massive workpieces present the usual problems of heat control, filler-metal flow and distortion. For such pieces (a filler pipe joined to an automotive gasoline tank is an example), soldering is usually selected for the joining method (if the strength is satisfactory), rather than brazing.

The machines and other equipment used in automatic torch brazing are basically the same as those described in the previous section on machine torch brazing. The use of burners rather than torches usually requires the installation of flowmeters and manometers for accurate flame control. An automatic setup lends itself more easily to multiple-joint or multiple-part brazing. Production rates are much higher.

Two types of face-feeding machine have made automatic torch brazing possible. They are the wire feeder and the paste feeder. Both machines are of the fixed-station type and are used in conjunction with a work-fixtured turntable or conveyor belt. Both are controlled by timers and are activated by a probe or limit microswitch that determines whether the approaching fixture is loaded. Various combinations of fluxing, filler-metal feeding and heating sequences are possible.

Wire Feeders. One type of wire feeder incorporates a double slide. The first slide advances the gas torches or burners into position. After a preset interval, the second slide advances wire-guide tips to the joint, and filler metal is fed, melting off on contact. When the correct amount of filler metal has been melted off, the wire is quickly retracted to prevent balling at the end. Heating is continued until the filler metal is distributed through the joint, and the torches or burners are then retracted.

In this system, flux is applied in either liquid or paste form at a previous station and gas fluxing is done through the torch or burner flames. The assembly is cooled by air or water at following stations.

The most critical part of the operation is the setting of the wire-feed rate to coincide with the wire melting rate; lack of coordination results in either an underfed joint or waste of filler metal (usually silver alloy). Cycle timing, slide motion and wire-feed rate are individually controlled by an electronic timing circuit.

Paste feeders apply a mixture of flux and powder filler metal to the joint or joints to be brazed. The paste is contained in a cylinder equipped with a piston to eject the paste through a nozzle. One or more cylinders are mounted on a single slide that enables the applicator to be positioned at the desired points of deposition.

The operating sequence, which is triggered by a microswitch striking the fixtured workpiece, consists in sliding the applicator into position, depositing a predetermined quantity of paste, and retracting. The workpiece is then moved through a series of burner stations where the flux is dried, melted and activated, and the filler metal is finally melted and distributed through the joint. Cycle timing, slide motion and paste feeding are controlled by electronic timing circuits. As in other automatic machines, stations are set up for loading, cooling and unloading. This system can also make use of gas fluxing, when it is required to keep the workpiece clean.

The following example describes the equipment used and the operations performed on an appliance part that required a high production rate.

Example 581. Automatic Torch Brazing of an Appliance Part on a 12-Station Turntable (Fig. 9)

A machine for high-production torch brazing of the joint between the low-carbon steel blades and shaft of an electric food beater required only manual loading. All other operations were controlled automatically, including ejection from the brazing fixture. The assembly, together with joint details, is shown in Fig. 9. The formed blades were fixed at one end of the shaft by riveting over a through-pin integral with the shaft. The four ends of the blades were notched to form a mitered cross, which fit precisely into the 0.045-in.-wide by 1/16-in.-deep annular groove cut in the shaft. Squeezing the blades together produced the desired joint configuration.

The machine consisted of a 12-station turntable with a station dwell time of 3.55 sec and a between-station indexing time of 1.25 sec, producing 750 assemblies per hour. The braze was made using a face-fed paste of BAg-1 silver alloy filler metal and flux. Heating was done with air – natural gas burners, with added gas fluxing to keep the assembly clean. Figure 9 shows the general arrangement of stations around the turntable and identifies the operations performed at each station. Turntable rotation was controlled by a timer that was set for station dwell time; indexing time was a machine constant. The following sequence describes the operations performed and the equipment used at each station:

Station 1, Loading. This station was equipped with an external loading device that slipped the beater blades into the circular opening in the locator arm of the holding fixture on the turntable. The loading device consisted of a cup-shaped die with four equally spaced slots to hold the beater blades in position for brazing and a hole in the center for the beater shaft. The die was fixed on a crossbar supported by two spring-loaded shafts, on which rode a sliding crossbar attached to a loading pin that was actuated by an air cylinder, as shown in Fig. 9.

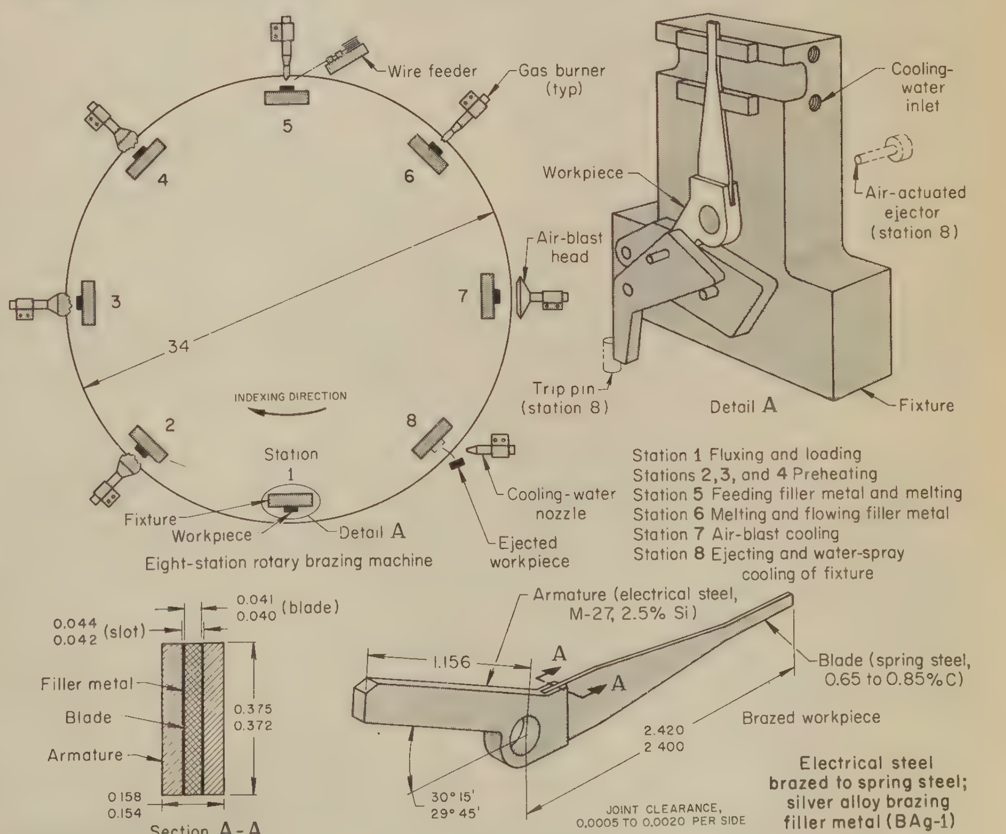
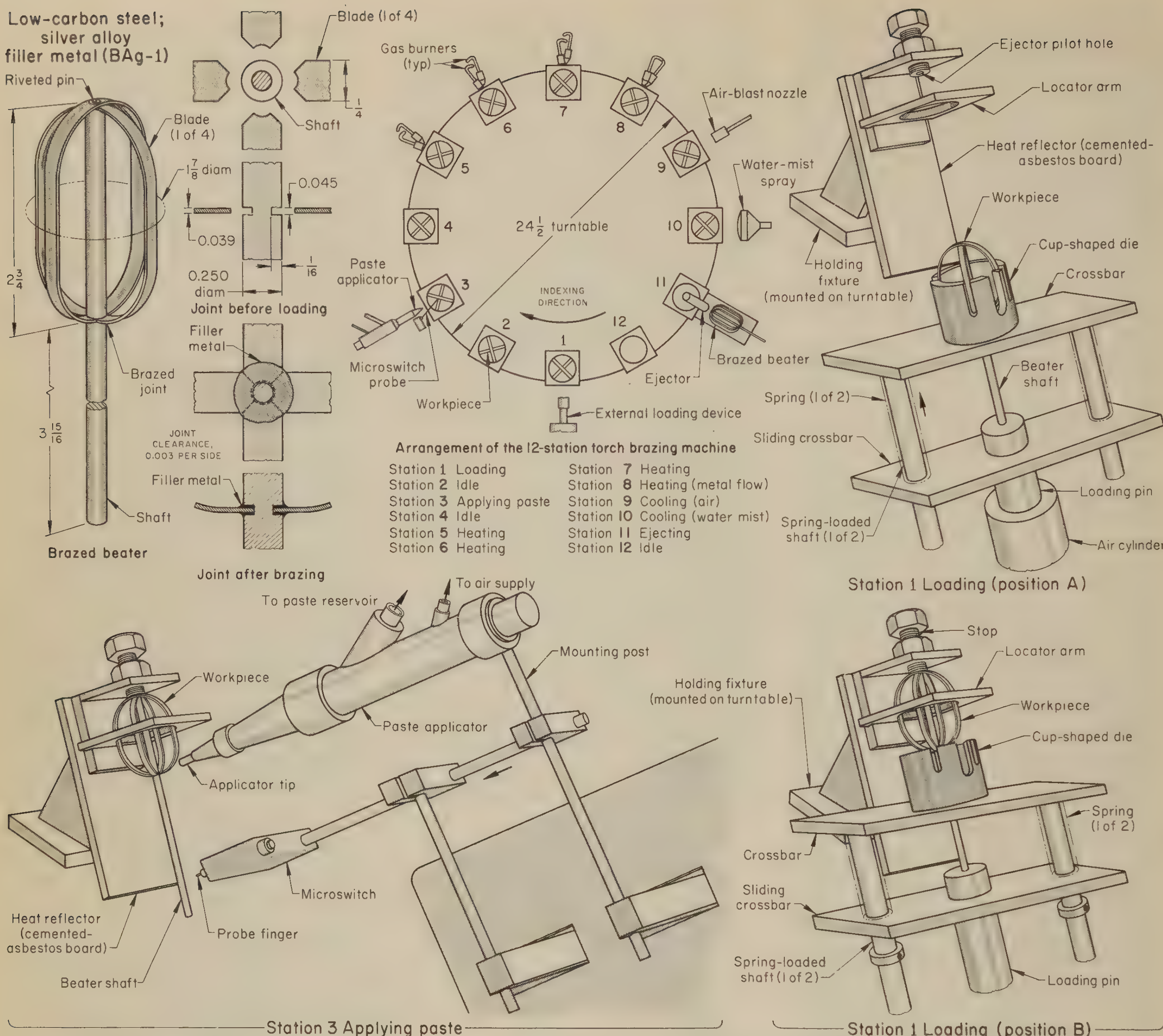


Fig. 8. Armature assembly and a schematic representation of the turntable machine used to braze 230 of the assemblies per hour (Example 580)



(Top, left) Food beater showing details of the joint before loading and after brazing. (Top, center) Schematic view of the turntable showing arrangement of the equipment used at 9 of the 12 stations and the operating sequence. (Right) Two views of the loading operation. In position A, the workpiece is fitted in the joint-forming die preparatory to loading; in position B, the workpiece is loaded into the locator arm of the holding fixture and the loading device has begun to retract. (Bottom, left) Paste applicator and microswitch probe that detected the presence of the workpiece and initiated the paste-feeding cycle. The workpiece was manually fitted in the loading die.

Fig. 9. Workpiece and the equipment and operating features of an automatic torch brazing machine of the paste feeder type (Example 581)

As the assembly was manually loaded into the die, the beater blades were squeezed together, positioning the ends in the joint. By pressing a button-switch, the operator caused the entire loading device to move upward. The spring-loaded shafts were end-stopped part way through the loading operation, but the sliding crossbar and loading pin continued to the end of the stroke, pushing the beater shaft until the four blades were engaged in the locator arm. When the loading device retracted, the machine indexed to the next station.

The turntable fixture, in addition to supporting the locator arm, had a bolt-and-locknut vertical stop with a hole through the center to permit entry of an ejector pin (station 11). A cemented-asbestos board over the fixture support served as a heat reflector. Fixture design is shown in Fig. 9.

Station 2, Idle. This station was idle to give the operator freedom from interference with the sizable apparatus at station 3.

Station 3, Paste Feeding. This station was equipped with a device consisting of a paste applicator and a microswitch, post-mounted on a slide, an air-pressurized paste reservoir, connected to the applicator by a plastic tube, and an air-supply tube to actuate the applicator piston. Figure 9 shows the general arrangement of these parts. This station also had a separate control panel with (*a*) a paste-pressure control knob set for 17 psi, (*b*) a meter indicating applicator operating pressure (40 psi), (*c*) a timer that controlled the paste-feed cycle, and (*d*) a cycle counter.

When the slide moved the applicator nozzle into position over the joint to be brazed, the probe finger of the microswitch was deflected by the workpiece. This closed the switch and started the timed cycle in which the piston ejected the correct amount of paste onto the joint. Approximately one ounce of paste supplied 200 parts.

Station 4, Idle. This station was idle to separate the paste-feeding equipment from the heat of the torches.

Stations 5 to 8, Heating. Each of these four stations had two air – natural gas burners with tips mounted on bendable copper tubing. In stations 5, 6 and 7, the tips directed the gas flames onto the beater shaft above and below the workpiece joint, for progressive heating. At station 8, the flames were directed so as to converge on the joint to complete the melting and obtain flow of the filler metal.

Air and natural gas were pumped, metered and mixed in a combustion control unit mounted in the base of the machine. The ratio of air to natural gas was 9 to 1. The supply of natural gas was monitored by a flowmeter; a manometer indicated the pressure of the gas mixture in the burners.

Station 9, Cooling. This station was fitted with an air-blast nozzle for cooling the workpiece.

Station 10, Cooling. The workpiece was further cooled with a water-mist spray.

Station 11, Ejection. When a fixture was indexed at this station, an air piston moved a pin down through the hole in the vertical stop, ejecting the part into a chute and out the side of the machine into a bin.

Station 12, Idle. This station was idle to give the operator freedom from interference with the collection bin.

After flux removal, the assemblies were chromium plated.

The main control panel for the machine had the following controls: emergency stop button, start button, a light signaling that paste was applied, a turntable-cycle on-off switch, an applicator on-off switch, and an on-off switch for the gas-combustion control unit.

Success with this machine indicated that the operator could easily load two beaters at one time, using both hands. Accordingly, a machine with 12 duplex stations was installed. Although larger and more complex than the machine described above, the equipment and operation were essentially the same. The new machine brazed 1400 to 1500 assemblies per hour.

Filler Metals

Silver brazing alloys and copper-zinc brazing alloys are the filler metals used in torch brazing of low-carbon and low-alloy steels. The product forms, nominal compositions, and the melting and brazing temperature ranges of the filler metals most frequently used are given in Table 1.

Choice of filler-metal form depends mainly on the joint design and the method of assembly. The amount of filler metal used can be controlled accurately by the use of preformed shapes bent from wire or blanked from strip. These can be preplaced in and around joints of various designs, in a manner that will enhance flow and complete filling of the joint.

Filler metal in powder form is often used, although if it is used on the exterior of the joint some provision must be made to hold it in place. One method is first to brush the joint with paste flux and then to dust the filler-metal powder lightly onto the flux while it is still wet. Another method is to mix the powder with flux and a binder to form a paste, which is then applied by brushing or face feeding through an applicator. Rod and wire can be manually face fed; automatic wire face-feeding equipment and paste-applying equipment are also available, as described earlier.

Silver Alloy Filler Metals

Silver alloys BAg-1 through 7 are used for torch brazing most types of steel to themselves or to other metals, except aluminum and magnesium, and are available in several product forms. (Alloys BAg-8 through 19 are used chiefly in furnace brazing.)

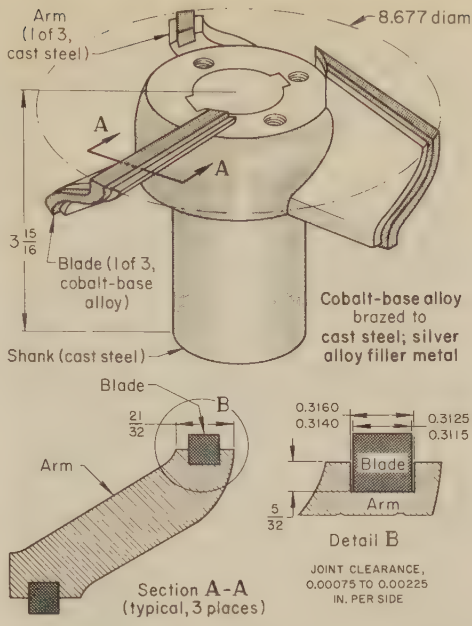


Fig. 10. Cutting impeller, with inserted blades of cobalt-base alloy, that performed satisfactorily in service only after joint clearances were controlled in brazing (Example 582)

The most frequently used alloys of the group shown in Table 1 are BAg-1, 1a and 3; the first two are outstanding for high fluidity, low melting temperature and narrow melting range. BAg-1 is much preferred for fast-cycle torch brazing, especially for automatic torch brazing with low-cost air – natural gas heating. The BAg-3 alloy contains nickel for improved wettability when brazing tungsten carbide (tool tips), and has lower fluidity for bridging larger joint clearances. BAg-2 and 2a are similar to 1 and 1a but contain less silver and are therefore cheaper; they also have a somewhat wider melting range.

These filler metals contain cadmium, which is added to depress the melting range and to improve flow properties. Because cadmium fumes are toxic, industrial brazing installations must be provided with adequate ventilation as described in the section on Equipment for Manual Torch Brazing. Federal regulations also stipulate that cadmium-bearing filler metals and their toxic properties be identified by a suitable warning label, because of the possibility of home and farm applications.

BAg-4 through 7 are cadmium free, a requirement for some food-processing applications. BAg-4, containing some nickel and being freer flowing than BAg-3, is used for brazing carbide tool tips. BAg-5 and 6 are widely used on electrical and food equipment. The melting range of BAg-7 is the lowest and narrowest in temperature of the cadmium-free alloys; containing tin, BAg-7 produces a white color that matches steel, in contrast to the somewhat yellowish color produced by the other silver alloys.

Joint clearances of 0.002 to 0.005 in. are often recommended for silver alloy filler metals. However, the clearances used in torch brazing vary considerably, as is seen by comparing Examples 576, 577, 580, 582, 584 and 586 in this article. Because joint clearance is a factor in capillary flow, too little or too much clearance affects filler-metal distribution, which affects joint strength (see page 607 in Furnace Brazing).

Maintaining consistently proper clearances is particularly important in automatic face-feeding operations. Some latitude is possible in face-fed manual torch brazing, especially if joint strength is not critical.

Where joint strength is critical, a poor fit, even if not apparent in the completed joint, is likely to show up in service. In the example that follows, the brazed joint was subjected in service to shock and fatigue loads, but no systematic provision for control of joint clearance was made until failures were reported.

Example 582. Specification of Clearance To Improve Reliability of Silver Brazed Joints (Fig. 10)

The cutting impeller shown in Fig. 10 was composed of a cast steel body consisting of a shank and three arms, each of which contained blades made of a cobalt-base alloy (30 Cr, 18.5 W, 3.5 Ni, 2.5 Fe, 2.0 C, 6.0 other). The blades were cut from 5⁄16-in. square wire, inserted into grooves in the arms, and joined to the arms by torch brazing.

Originally, the grooves were machined 5⁄16 in. wide by 5⁄32 in. deep with no specification on tolerance. During assembly, the blades were ground and fitted by trial and error, and held in position by movable C-clamps. Joint clearance was left to the judgment of the operator.

A silver alloy and a proprietary flux were selected for manual brazing with an oxyacetylene torch. The silver alloy filler metal was a cadmium-free, low-melting (1130 F) type with whitish color, similar to BAg-7. During heating, the torch flame

Table 1. Filler Metals for Torch Brazing Low-Carbon and Low-Alloy Steels (a)

AWS classification	Product form	Nominal composition, %										Temperature, F		
		Ag	Cu	Zn	Cd	Ni	Sn	Fe	Mn	Si	P	Solidus	Liquidus	Brazing
Silver Alloys														
BAg-1	Strip, wire, powder	45	15	16	24	...	...	...	...	...	...	1125	1145	1145 to 1400
BAg-1a	Strip, wire, powder	50	15.5	16.5	18	...	...	...	...	...	...	1160	1175	1175 to 1400
BAg-2	Strip, wire, powder	35	26	21	18	...	...	...	...	...	...	1125	1295	1295 to 1550
BAg-2a	Strip, wire, powder	30	27	23	20	...	...	...	...	...	...	1125	1310	1310 to 1550
BAg-3	Strip, wire, powder	50	15.5	15.5	16	3.0	...	...	...	...	...	1170	1270	1270 to 1500
BAg-4	Strip, wire	40	30	28	...	2.0	...	...	...	...	...	1240	1435	1435 to 1650
BAg-5	Strip, wire	45	30	25	...	...	...	...	...	...	...	1250	1370	1370 to 1550
BAg-6	Strip, wire	50	34	16	...	...	...	...	...	...	...	1270	1425	1425 to 1600
BAg-7	Strip, wire	56	22	17	...	...	5.0	...	...	...	...	1145	1205	1205 to 1400
Copper-Zinc Alloys														
RBCuZn-A(b)	Strip, rod, wire	...	59	40	...	...	0.6	...	...	...	...	1630	1650	1670 to 1750
RBCuZn-D(b)	Strip, rod, wire	...	48	41	...	10.0	...	...	...	0.15	0.25	1690	1715	1720 to 1800
RCuZn-B(c)	Rod	...	58	38	...	0.5	0.95	0.7	0.25	0.08	...	1590	1620	...
RCuZn-C(c)	Rod	...	58	39	...	...	0.95	0.7	0.25	0.08	...	1595	1620	...

(a) Abstracted from the mandatory and nonmandatory sections of AWS A5.7-69, AWS A5.8-69, and other sources. (b) Classified for braze welding and brazing. (c) Classified for braze welding.

Table 2. Flux Types Commonly Used in Torch Brazing of Low-Carbon and Low-Alloy Steels

AWS type	Useful temperature range, F	Principal constituents	Available forms	Applicable filler metals
3A	1050 to 1600	Boric acid; borates; fluorides; fluoborates; wetting agent	Powder; paste; liquid	BAg-1 through 7
3B	1350 to 2100	Boric acid; borates; fluorides; fluoborates; wetting agent	Powder; paste; liquid	BAg-1 through 7, RBCuZn
5	1400 to 2200	Borax; boric acid; borates; wetting agent	Powder; paste; liquid	RBCuZn

was applied to the steel body only, until brazing temperature was reached. A 1/16-in.-diam wire of filler metal was then fed and melted into the joint, the clamps being moved as necessary. Production time for the three arms was ½ hr. Visual inspection indicated no problems. The assemblies were washed in water, wire brushed and ground to size.

In service, however, the blades often came loose and subsequently broke. Investigation showed a large variation in joint clearance. The blade material was then obtained ground to size, 0.3120 ± 0.0005 in. square. Dimensions of the groove were changed to the size and tolerance shown in Fig. 10, which gave a total clearance of 0.0015 to 0.0045 in. at room temperature. Since that change, no service failures have been reported.

Copper-Zinc Filler Metals

Copper-zinc filler metals are extensively used in manual torch brazing and braze welding of low-carbon and low-alloy steels. They can also be used to join nickel-base and copper-nickel alloys to themselves or to steel, where corrosion resistance is not required. Table 1 gives the nominal composition and melting characteristics of four copper-zinc alloys used as filler metals. The two RB types are classified for braze welding and brazing; the two R types for braze welding only. The R types are included in Table 1 to clarify a distinction among the four standard copper-zinc filler metals that is often overlooked; only the two RB types are used in torch brazing, but all four copper-zinc filler metals can be used in braze welding.

Copper-zinc filler metals have higher melting and brazing temperatures than silver brazing alloys. However, overheating must be avoided, because of their high zinc content. When the alloys are overheated, zinc vaporizes ("fumes"), causing voids in the joint. RBCuZn-A, often called naval brass or bronze, produces some zinc fuming and is brassy in color. RBCuZn-D, containing 10% nickel, is often called nickel silver, because of its whitish color, although it contains no silver. RBCuZn-D is often selected for its low fuming and high strength, as well as for its good color match with steel. Because of its high brazing temperature, it is possible, when brazing some heat treatable steels, to combine brazing with heating for hardening. Chromium-molybdenum steels have been brazed and heat treated in this manner. Both RB types of filler metal have a relatively narrow melting range. When used for torch brazing, joint clearances of 0.002 to 0.005 in. are recommended. These filler metals are also available as pastes for automatic torch brazing.

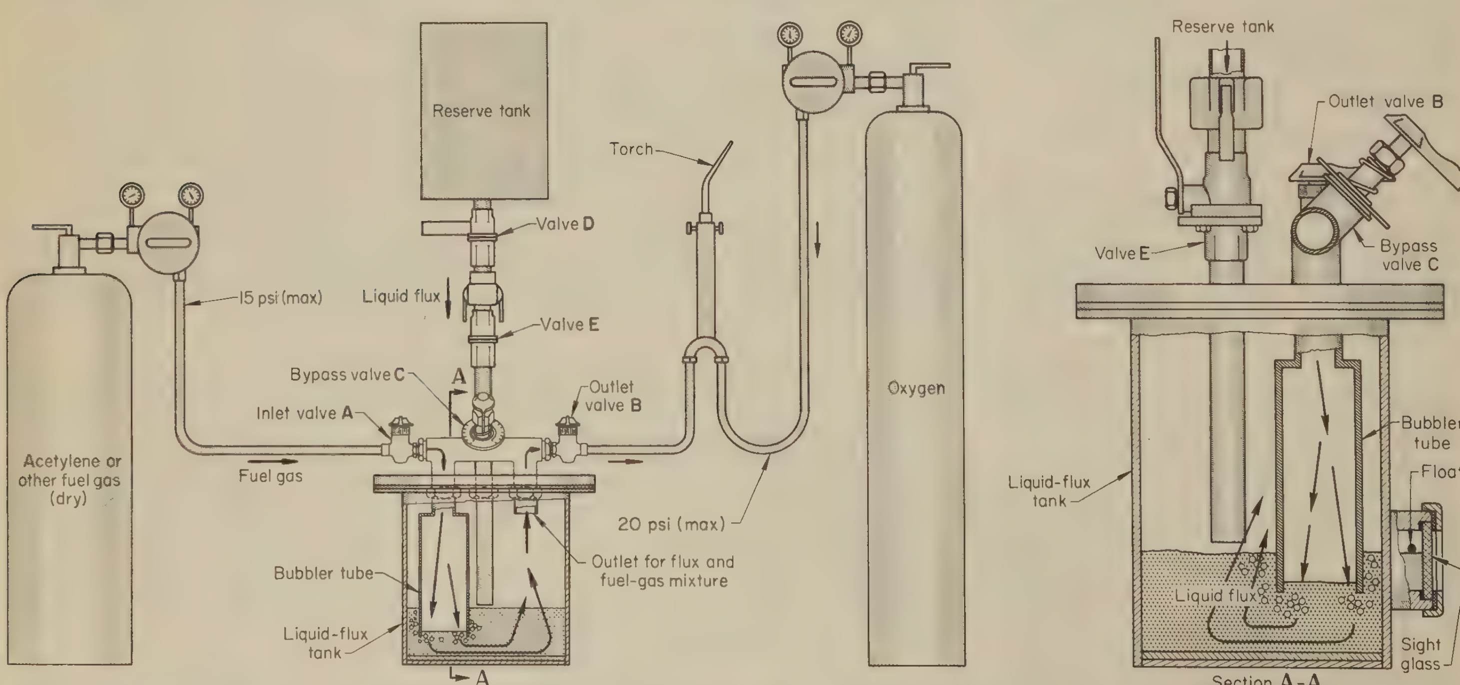
Fluxes

Surface oxide films inhibit the wetting of the base metal by the filler metal and therefore the capillary flow of the filler metal in the joint; they also prevent the formation of a true metal-to-metal braze bond. Fluxes must have sufficient chemical and physical activity to reduce or dissolve the thin surface films without attacking the base metal severely. They are not made to dissolve greases or dirt. For these reasons, fluxes are not intended to serve as a substitute for prebraze cleaning or for removal of heavy oxide films. The chemical reactivity of a flux with the oxides and other compounds encountered on the surface of the base metal varies according to the stability of the compounds.

Because the heat of brazing accelerates the formation of films, such as oxides, fluxes must also melt and flow freely over joint surfaces to shield the metal from the atmosphere under the torch brazing conditions. In addition, because different filler metals vary as to melting range and brazing temperature, fluxes must maintain their stability and effectiveness throughout the brazing temperature range of the filler metal being used.

Finally, the density, viscosity, and surface tension of the molten flux must be low enough to enable the molten filler metal to replace the flux on the joint surfaces by capillary flow. It is also important that fluxes be easy to remove after brazing, preferably by washing in hot water.

Flux Constituents. Brazing fluxes are available chiefly as proprietary formulations; there are no standard specifications, such as those for filler metals. A general list of the compounds used in brazing fluxes is given below; of these, the boron and fluorine compounds are the active deoxidizing constituents used in fluxes for the torch brazing of steel.



Fuel gas flows through the inlet valve A into the liquid-flux tank, where it bubbles through the flux, entrains some of it and carries it through the outlet valve B to the torch. The bypass valve C controls the proportion of fuel gas entering the bubble chamber to provide rich or lean fluxing mixtures. Valves D and E are for refilling the liquid-flux tank and for removing the reserve tank for remote filling without stopping the operation. Joints must be sealed to prevent moisture pickup from air, which would cause precipitation of flux and clogging of lines.

Fig. 11. Gas fluxing hook-up for a manual brazing station

Fused borax is a high-melting material that is active at high temperatures. It is seldom used in low-melting brazing fluxes.

Borates melt at 1400 F or higher. They have moderately high viscosity and must be used with other constitutents. They are potent oxide solvents and protect against oxidation for long periods.

Fluorides react readily with most metallic oxides at high temperatures, and are used in fluxes as cleaning agents. They are especially useful in counteracting refractory oxides, such as chromium oxide and aluminum oxide. They also increase the fluidity of molten borates.

Chlorides function in much the same manner as fluorides, but at a lower temperature. They must be used carefully, because at high temperatures they may oxidize the work metal. Chlorides are used to depress the melting temperature of fluoride-base fluxes, and are useful in brazing aluminum.

Fluoborates react in somewhat the same way as borates, but they do not give as long-lasting protection. They flow better in the molten state than the straight borates, and have superior oxide-dissolving properties. Fluoborates are used in combination with borates and alkaline compounds such as carbonates.

Fluosilicaborates have a somewhat higher melting range than fluoborates. They cover and adhere to surfaces well, but they are more limited in use than fluoborates because of their high melting point.

Hydroxides of sodium and potassium absorb moisture from the air, and therefore are used in fluxes for special applications only. Even small amounts in other fluxing agents can cause difficulty and limit storage life in humid environments. They raise the useful working temperature of fluxes and are used in fluxes for brazing molybdenum-bearing tool steels.

Boric acid is used in the conventional and in the calcined form. The calcined form has a somewhat higher melting point. Both forms promote friability to help facilitate the removal of the glasslike flux residue that remains after brazing. The melting range of boric acid is lower than that of the borates, but higher than that of the fluorides.

Wetting agents are used in paste and liquid fluxes to promote the flow and spread of the flux on the work metal. The agents that are used must not interfere with the normal functions of the flux.

Water is present in brazing fluxes either as water of hydration in the various chemicals, or as an addition to make the flux into a paste or a liquid. Water of hydration is removed by calcining the chemical that contains it. Water that is used to dilute fluxes must be tested for mineral content. Excessively hard water should be avoided. Sometimes alcohol is substituted for water, or demineralized water is used.

Flux Types. For torch brazing of low-carbon and low-alloy steels, fluxes can be grouped roughly into three general types, as shown in Table 2. The flux constituents are formulated so that their useful temperature range meets the applicable filler-metal temperature requirements. Boron compounds are present in all three types because of their stability. To be compatible with the silver alloy filler metals, fluorine compounds are added to lower the useful temperature range and the viscosity of the flux, as indicated by type 3A. Boron compounds alone are used in type 5 flux because the higher useful temperature range and viscosity are compatible with the copper-zinc filler metals. Type 3B flux falls between type 3A and type 5 in useful temperature range, and represents a second choice for either filler metal, in the torch brazing of steel.

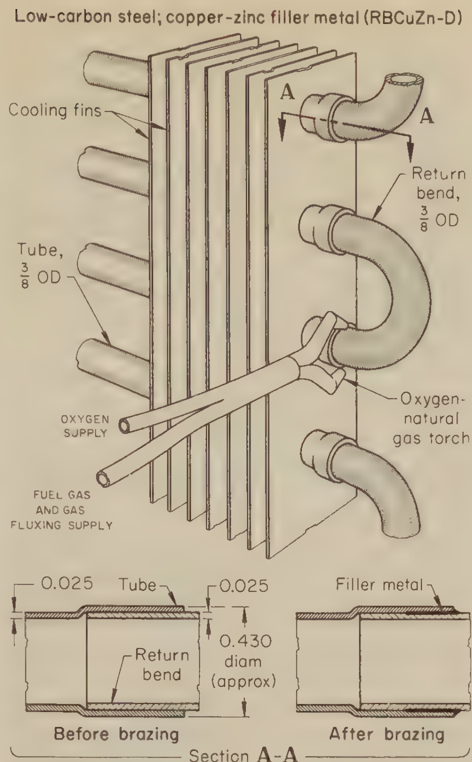


Fig. 12. Portion of an oil cooler showing the method used for brazing return-bend joints. Copper-zinc alloy filler metal with gas fluxing proved less costly than silver alloy filler metal with liquid flux. (Example 583)

Gas Fluxing. In some applications of manual and automatic torch brazing, more efficient production can be realized by applying flux directly through the gas flame. This is accomplished by bubbling the fuel gas through a small tank containing the flux in the form of a volatile liquid. A typical gas-fluxing assembly is shown in Fig. 11. Vaporized flux is entrained with the fuel gas, which flows to a conventional torch or burner, mixes with oxygen (or air) and burns in the flame, depositing a thin, uniform film on the workpiece. In liquid form, the flux is a type of methyl borate produced from methanol, boric acid and diluents, under moisture-free conditions. Its temperature range corresponds to flux type 3B (Table 2).

Any fuel gas that is free of water vapor can be used with gas fluxing. In the presence of water vapor, the fluxing agent (boric acid) is precipitated in the form of a whitish, crystalline solid. This condition is prevented by installing a chemical drier (calcium chloride) in the line and by substituting ethylene glycol for the water used in flashback arresters. For best results, a neutral flame is used. Brazing is done using goggles with number 4, 5 or 6 green lenses, because the flux produces a brilliant green flame that masks the inner flame cone from view by the naked eye.

The flux can be deposited only on areas that the flame can reach. Gas fluxing has two principal uses:

1. In manual torch brazing and especially in braze welding of low-carbon steel, where rods of copper-zinc filler metal are used in joints having varying or relatively large clearances, the flux is used for brazing the joint and for protecting the base metal from oxidation. In such applications, gas fluxing eliminates the need for continually dipping the filler-metal rod in flux or for making use of the more costly flux-covered rods. For postbraze cleaning, the flux can be removed by washing in hot water (150 F). Cost savings are most significant in production braze welding operations.
2. In applications where joint clearances are closely held, and also in applications using silver alloy filler metals, a suitable flux (type 3A or 3B, Table 2) must be applied to the joint before heating. Under these conditions, gas fluxing is used mainly to protect the part from oxidation when surface appearance is important or when parts are to be subsequently plated. As an aid in fluxing, it also reduces the amount of paste flux that otherwise would be required and, in hand-fed operations, reduces the amount of silver alloy filler metal used.

Gas fluxing is also used in a variety of semiautomatic and automatic torch brazing equipment. In addition to its use in joining low-carbon steel, it is employed in brazing alloy steels, stainless steel, copper and copper alloys, and nickel alloys, and in joining these metals to each other.

Applications of gas fluxing in the torch brazing and braze welding of steel include automotive and machinery parts, bicycle and motorcycle frames, metal furniture, doors and partitions, and many kinds of special fixtures.

In one plant, a window bracket was made from a flat piece of cold rolled steel and a 2-in. length of tubing of the same kind of steel. At first, the assembly was torch brazed using a paste or powder flux with an RBCuZn-D rod. When the brackets were chromium plated after brazing, a rough, peeling area appeared next to the brazed joint.

A change was made to gas fluxing, using the same filler metal. Fillets were smooth and sound, and could be chromium plated satisfactorily. The cleanness of the joint made with gas fluxing was responsible for the better adhesion of the electroplate.

In another plant, the flow of subassemblies required for final assembly was processed through separate stations, each manned by a torch brazing operator. Highly skilled operators combined brazing and braze welding techniques for economy of time and motion, as described in Example 526, in the article on Oxyacetylene Braze Welding.

Changing from a silver alloy filler metal with a brushed-on flux to a copper alloy filler metal and gas fluxing may prove advantageous, as in the example that follows.

Example 583. Copper-Zinc Brazing With Gas Fluxing vs Silver Alloy Brazing With Paste Flux (Fig. 12)

Return bends on low-carbon steel oil-cooler tubes like those shown in Fig. 12 were formerly torch brazed using BAg-2 silver alloy filler metal and type 3A flux. The paste flux was brushed on after the tubes were assembled. The brazed assemblies had to be carefully flushed and dried, both inside and out, to remove corrosive flux residue. The joint was heated with a dual-tip torch fed by oxygen and natural gas to produce a flame temperature of about 3300 F. Filler metal was hand fed to the joint.

A change was made to RBCuZn-D filler metal and, at the same time, gas fluxing replaced the use of paste flux. The joints continued to be sound. The cost of the replacement filler metal was considerably lower than that of BAg-2, and the need for washing to remove flux residue was eliminated. In both methods, the actual heating time was about 3 sec.

Destructive tests showed that the joint appeared more like a braze weld. The flow of the copper-zinc filler metal through the joint was less complete than that of the silver alloy. However, hydrostatic and air leak tests on all production parts showed satisfactory joint quality.

Advantages of Torch Brazing

The advantages of torch brazing for several types of applications have been pointed out in examples in this article. In Examples 574, 575, 576 and 577, fixturing of the assembly was either not needed or simpler when torch brazing was used. The appearance of the joint was also a factor in the selection of torch brazing over welding in Example 576. Feasibility and cost determined the choice in Examples 578 and 580. In Examples 578, 584 and 585, production quantity was too low to warrant investment in equipment for other brazing processes. In Example 586, torch brazing was selected because it localized the heating. Induction brazing with a single wraparound inductor would have heated a wider band, which might have resulted in damage to the part.

Example 584. Torch Brazing Experimental Assemblies (Fig. 13)

Only three experimental cylinder-cap assemblies of the size shown in Fig. 13 were needed. The most suitable method for joining the low-carbon steel components would have been either induction brazing with silver alloy or furnace brazing with copper. But the equipment was not available and the small number of parts needed did not warrant its procurement. The three assemblies were therefore torch brazed.

The filler metal used was silver alloy BAg-1a, and the flux was type 3A. The assemblies were positioned cap-end down, and the filler metal was hand fed to the joint. Diametral clearance between cylinder and caps ranged between 0.000 and 0.006 in.

Example 585. Use of Torch Brazing To Attach a Reference Clip to a Vane Assembly (Fig. 14)

The air-vane assembly shown in Fig. 14 had to be carefully positioned during a subsequent operation, and therefore a calibrating surface was needed. This was supplied by brazing a small protractor clip to the end of the vane. Because of the thinness of the skin and the criticality of the angle of the protractor clip, care had to be taken not to overheat the joint area.

The surfaces of the low-carbon steel components were first cleaned with a solvent to remove oil and grease, and then further cleaned with an abrasive wheel to remove oxides and scale. Type 3A flux was applied to the cleaned surfaces.

The protractor clip was positioned carefully and bolted to hold it in position. The clip and surrounding surface were heated by the torch to drive off moisture and to activate the flux. As the flux became active, silver alloy filler metal, BAg-1, in wire form was hand fed to the joint. The torch was removed as soon as the filler metal flowed into the joint. When the assembly cooled, residual flux was removed by washing, the joint was scrubbed with a wire brush, and the assembly was dried and rustproofed.

The reason for torch brazing rather than using another brazing method was that only ten assemblies were to be made. In addition, torch brazing made it possible to observe the operation as heat and filler metal were applied.

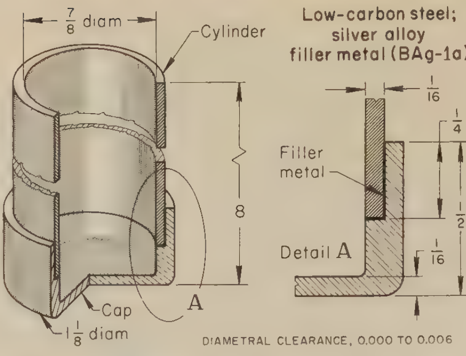


Fig. 13. Cylinder-cap assembly that was torch brazed because quantity to be brazed was low (Example 584)

Example 586. Use of Torch Brazing To Localize Heating (Fig. 15)

The low-carbon steel assembly shown in Fig. 15 was part of an electrical connector. Three small plugs like the one shown in detail A were distributed around the inner wall. They were to be used for locating purposes. The positions of the plugs were staggered around the circumference of the connector barrel and were approximately $\frac{1}{4}$ in. from a hermetic seal, which had been brazed in place in a previous operation.

The plugs had to be brazed into place without impairing the hermetic seal. There were two possibilities: induction brazing, in which a zone all the way around the barrel would be heated and the three plugs would be brazed simultaneously; and torch brazing, in which each of the plugs would be brazed individually.

The possibility that the induction-heated zone might spread wide enough to affect the hermetic seal led to the choice of torch brazing, even though it was more time consuming. A small spot inductor could have been used to braze the plugs one at a time, but the probable saving in brazing time did not warrant the investment in equipment.

The plugs had $\frac{1}{32}$-in.-diam shanks that were press fitted into holes in the connector barrel. Length of the shanks was less than the thickness of the barrel wall, so a small well was left at the outside end of each plug to retain flux and filler metal; each was brazed and cooled individually.

The filler metal used in brazing both the seal and the plugs was BAg-3; flux was 3A.

Removal of Flux After Torch Brazing

There are five major reasons for removing residual flux after brazing: (*a*) the joint cannot be inspected for soundness until the cover of flux residue is removed; (*b*) the joint may be bound together by the flux in the semblance of a brazed joint, only to break apart later in service; (*c*) in fluid or pressure service, the flux may block pinholes that might withstand a pressure test, but would leak soon after being placed in service; (*d*) if left on the joint, the flux attracts available water, resulting in oxidation and corrosion; and (*e*) painting, coating or plating cannot be done satisfactorily on areas covered with flux residue.

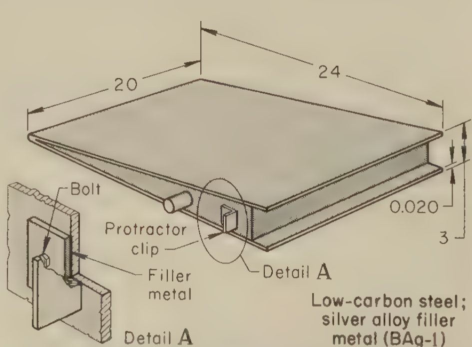


Fig. 14. Air-vane assembly on which protractor clip was brazed for alignment in subsequent assembly (Example 585)

If parts have been well cleaned before brazing and not overheated during brazing, flux residue can usually be removed by a hot water rinse followed by thorough drying. To avoid corrosion, flux removal should be delayed no more than 48 hr.

A quick method of removing glasslike residues is to quench the joint in cold water after brazing and thus to crack off the deposit by thermal shock. However, in some applications, such treatment may cause distortion of the brazed assembly.

Scrubbing, applying a steam jet, and most of the standard abrasive techniques, such as wire brushing and abrasive blasting, are also used to dislodge stubborn flux residues, provided the operation does not impair the function of the assembly.

When flux cannot be removed from steel assemblies by rinsing in cold or hot water, a cold 5% solution of sulfuric acid will prove more effective. The solution may be warmed to accelerate the action, provided care is taken to prevent excessive attack on the assembly. A small addition of sodium dichromate to the solution makes the action even faster, but the time of immersion must be carefully controlled to avoid the greater risk of etching the steel.

Phosphate solutions similar to those used for cleaning steel are effective flux removers and have the added advantage of giving carbon steel assemblies a temporary protective coating. However, the coating will hamper subsequent brazing operations.

Boric acid, as applied in gas fluxing, can be removed by washing in clean water heated to at least 150 F. (Boric acid is only slightly soluble in cold water.)

Mixed borax and boric acid fluxes are more difficult to remove than other types. Fortunately, moisture absorption and corrosion are minimal with borax fluxes. In fact, rather than risk damage to delicate assemblies, such as electronic components, when mixed borax and boric acid fluxes are used the flux is sometimes allowed to remain after brazing. The manufacturer accepts the possibility of some corrosion occurring and some imperfect joints being hidden under the flux.

These fluxes can be removed by quenching, shot blasting, sand blasting, chipping, filing, scraping and wire brushing. The rate of solution in water is slow, and even if a dilute sulfuric acid solution is used, the necessary period of immersion may be inconveniently long for production work.

Fluoride fluxes are soluble in water and are much easier to remove than borax fluxes. Holding under running

cold water while brushing with a wire or bristle brush will usually suffice. Alternatively, the assemblies may be boiled in water for a few minutes, and then rinsed in cold water. Dilute sulfuric acid solutions and phosphate solutions can also be used for quicker results. The residue of fluoride fluxes is hygroscopic, and if the assembly is not quenched after brazing, it is often advantageous to postpone the postbrazing cleaning for 24 hr. Under normal atmospheric conditions, the residue will absorb moisture during this period and will become more readily soluble in any of the solvents previously mentioned. Flux removal should never be delayed for more than 24 hr. In 48 hr, many types of steel will begin to corrode.

If a fluoride flux is difficult to remove, the cause can usually be traced to the brazing operation. If too little flux is used, the residue is a hard, cokelike oxide. If the flux is heated above its rated operating temperature, or for too long a time, it is likely to leave a hard, glasslike residue similar to that left by borax fluxes.

Care should be taken to prevent fluoride residues from entering the body via mouth or skin openings. Gloves should be worn, and the hands washed well before handling food.

Preparation for Plating. If the assembly is to be electroplated, a suitable treatment is immersion in a solution of 5% sulfuric acid and 3% sodium or potassium dichromate followed by a water rinse and a hydrochloric acid pickle. The anodic treatment that is normally used for cleaning before plating will remove the last traces of flux, but should not be used for removal of all flux because the electrolyte will quickly become contaminated with flux.

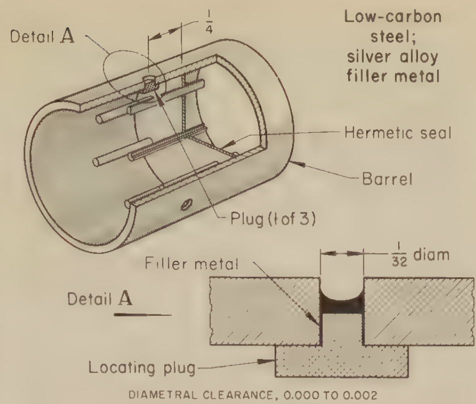


Fig. 15. Connector assembly with locating plugs that were torch brazed in position one at a time to avoid heat damage to a hermetic seal (Example 586)

Safety

The use of safe practices to avoid accidents, and the rules for applying these practices, are discussed in the section on Safety on page 578.

Failure to follow simple rules is a major cause of accidents in brazing and welding operations. Gases must be shut off at the regulators; gas savers should never be used to shut off supply for more than a short time. Even a small leak in the hose line can lead to a potentially dangerous accumulation of gases after working hours, when exhaust fans are not in operation.

Other Examples of Torch Brazing

Other articles in this volume contain examples involving torch brazing, either as the original method of joining that was superseded by a more satisfactory method, or as the preferred method for joining a particular type of alloy or a particular structure.

The following table lists nine such examples, with brief descriptions of the members joined. In each case, a silver-base alloy was used as the filler metal. Manual torch brazing was used in all cases except for Example 568, where the operation was automatic.

Other Examples of Torch Brazing in This Volume

Example 565: Lever assembly of low-carbon steel sheet and tubing
Example 566: Can-opener blade assembly of low-carbon steel sheet, tube and bar
Example 567: Plate-and-bushing assembly of low-carbon steel
Example 568: Shaft pin of free-machining steel to low-carbon steel lever arm
Example 592: Joining the corner seams of a formed low-carbon steel letter tray
Example 615: Tubes of type 304L stainless steel to type 304L sleeve for high-vacuum service (cadmium-free filler metal)
Example 627: Pure nickel tube to type 304 stainless steel tube
Example 629: Ten joints in a stainless steel temperature sensor; type 302 to type 303, and types 302 and 304 to 304
Example 630: Copper alloy 230 (red brass, 85%) wave-guide tube to flange of type 304 stainless steel

Induction Brazing of Steel

*By the ASM Committee on Brazing of Steel**

INDUCTION BRAZING is a process in which the surfaces of components to be joined are selectively heated to brazing temperature by electrical energy supplied from an induction heating unit. The energy is transmitted to the workpiece by induction, rather than by electrical connection, using an inductor or work coil. Heating is the result of eddy currents or I^2R losses in the work metal which, by virtue of its electrical resistivity and the flow of induced alternating current through it, generates heat. When the work metal being heated is ferromagnetic, as are most steels, some slight additional heating results from hysteresis. However, all heating due to hysteresis ceases when the temperature of the work metal is raised to the Curie point (about 1420 F). Above this temperature, heating by electrical resistance continues at a reduced rate as the temperature rises.

Most of the heat induced in the workpiece by electric current is limited to a thin surface layer close to the inductor. Distribution of heat to other areas of the workpiece depends on conduction. In general, heat flow by conduction, although fairly rapid, is minimized by the rapidity at which induction heating takes place. The depth of heating by induction depends mainly on the frequency of the alternating current.

As the frequency is increased, both the theoretical depth of current penetration and the depth of the heated zone in the workpiece decrease. For example, the theoretical depth of current penetration is about 0.035 in. at a frequency of 3 kHz but decreases to about 0.003 in. at 500 kHz†.

Frequency Range. Frequencies used for induction brazing can range from the powerline frequency of 60 Hz to approximately 450 kHz. The higher frequencies should be selected when shallow heat penetration is desired. In the induction heating of steel for surface hardening, shallow heat penetration at high power inputs is generally desirable for rapid heating and control of depth of heating. In the brazing of steel components, however, deeper and more uniform heating of the two parallel surfaces that will form the joint may be preferable, and the advantages of a high operating frequency, such as 450 kHz, may be more suitable for the brazing of nonferrous metals or the brazing of steel to a nonferrous metal or a nonmagnetic (austenitic) steel. The role of frequency in induction brazing is considered in detail in the section on Selection of Frequency in this article. For the majority of brazing applications, the frequencies used are seldom below 10 kHz, the peak frequency obtainable from motor-generator power-supply units.

Process Capabilities

The primary advantage that induction brazing has over other brazing processes is high-speed localized heating, which minimizes oxidation and thus reduces cleaning requirements. Because the heating is localized, warpage is often less than when the entire assembly is heated, and the nature and extent of metallurgical changes, such as the softening of cold worked or heat treated metal, are also minimized.

*For committee list, see p 593. Some examples in this article were contributed by other Metals Handbook welding and brazing committees.

†Hz = Hertz, or cycles per second; kHz = kiloHertz, or kilocycles per second.

Most of the variables in induction brazing are machine controlled. Therefore, operators require a minimum of training and skill. Induction brazing is capable of making clean, neat joints without excessive spatter or excessive flow of filler metal to areas where it is neither needed nor wanted. This latter capability accounts, in part, for the extensive use of the process in the electronics and electrical industries. For instance, in induction brazing of the electrical-coupling assembly shown in Fig. 1, nickel-plated ceramic pins, by which electrical connections were made, were not bridged when brazed into the diaphragm seal of the coupling body. (Bridging, in this application, refers to the flow of filler metal from one pin to another, thereby establishing a silver connection between pins.) The coupling body was machined from ⅝-in.-diam free-machining 1010 steel bar stock. The pins were plated with nickel, to make a brazeable surface. Holes through the diaphragm were chamfered to obtain a good fillet of filler metal without excessive overflow. A small amount of AWS type 3A flux was applied, and the filler metal (BAg-1) was carefully measured and preplaced to avoid excessive flow and bridging of the ceramic pins. Heat was closely controlled by timing each cycle.

Metals Brazed. With the exception of aluminum and magnesium, most of the common metals and alloys that can be joined by other brazing processes can be brazed satisfactorily by induction. Other exceptions, based largely on feasibility and cost, usually involve brazing at extremely high temperatures in vacuum or a protective atmosphere. Although it is possible to induction braze in vacuum or in some protective atmospheres, such procedures are costly and are limited to specialized applications. Most induction brazing is done without the protection of a prepared atmosphere. Therefore, the heating and cooling must be rapid and the temperature attained must be relatively low (seldom higher than 1550 F), or the workpieces will oxidize excessively beyond the flux-protected joint.

Dissimilar metals can be induction brazed, although special techniques must be employed to equalize differences in heating rates when a magnetic metal is induction brazed to a nonmagnetic metal, or to equalize differences in coefficients of thermal expansion of dissimilar metals being induction brazed (see discussion and Example 590 in the section "Brazing of Dissimilar Metals", on page 639).

Size Limitations. Induction brazing is most conveniently applied to small and medium-size assemblies. Brazing large assemblies, such as cylindrical bodies several feet in diameter, would entail major problems in coil construction, coupling and circuit balancing, even with an adequate power supply.

Brazing temperature also may impose a limit on the size of assembly that can be brazed by induction. Power requirements increase with an increase in the area to be heated and the required brazing temperature.

Nevertheless, the practical limit on the maximum size of an assembly for induction brazing normally exceeds that for furnace brazing. In furnace brazing, the entire assembly must be heated to the brazing temperature, whereas in induction brazing, the inductor is designed to restrict heating to the joint area.

Shape Limitations. Assemblies of almost any shape can be heated for brazing by induction, depending primarily on limitations imposed by construction of a suitable inductor, matching the impedance of the inductor and setup with the output characteristics of the power supply, efficiency in heating, and cost. Although many inductors of intricate and unusual design have been constructed, practical limits are entailed in the bending and forming of copper tubing of a given diameter and wall thickness, as well as in providing the inductor with enough cooling water to prevent overheating, and in matching impedances.

Some of the problems associated with large assemblies have been overcome by rotating, or otherwise moving, the workpiece in relation to the inductor to develop an intricate heating pattern with a relatively simple inductor. In this manner, for example, a cylindrical object can be heated evenly while it is rotating within a simple, nonconforming "hairpin" inductor.

Maximum efficiency in heating is generally obtained when heating the external surface of a cylinder, using a simple ring inductor of one or more turns that surrounds the external surface. Such an inductor is also among the easiest to construct and to cool. In contrast, heating the internal surface of a hollow cylinder by locating the inductor inside the cylinder is considerably less efficient and requires a much larger power input to heat the same volume of metal in a given time. Nevertheless, such coils are often used when adequate power is available.

At the higher operating frequencies, such as those provided by vacuum-tube power supplies, workpieces that have sharp corners or projections such as threads are susceptible to damage in induction brazing, because the crests or points will overheat, and may even melt, before the joint reaches brazing temperature. There are techniques, however, that limit damage to thread profiles (see Example 595).

Although induction brazing is by no means limited to assemblies that are self-jigging, this design feature, as in furnace brazing, will often eliminate the need for special fixturing. Assemblies that are not self-jigging by virtue of design may often be temporarily held together by staking or tack welding. The use of fixtures in induction brazing is not uncommon, but may impose special requirements regarding the selection of materials from which the fixtures are to be made. For fixtures that are to be located close to (2 in. or closer) any portion of the inductor or connections leading to the inductor, heat-resisting nonmetallic materials, such as cemented-asbestos board, ceramics and quartz are preferred. Aluminum and copper are also useful fixture materials, provided that they are far enough from the inductor not to be heated by it. Fixtures that are allowed to become heated will deteriorate and will detract from the efficiency of the brazing operation.

Matching Impedance. An important limitation in all induction heating operations entails the requirement for matching impedance. All of the characteristics of the inductor (or work coil), including its diameter, number of turns, length, coupling with the work load and operating frequency, together with work-load variables such as the electrical resistivity of the workpiece, combine to constitute a factor known as impedance. Heating the workpiece depends on obtaining sufficient power in the inductor, which, in turn, depends on matching the impedance of the setup (inductor and workpiece) with the output characteristics of the power supply (generator or oscillator).

In essence, the circuit that constitutes the inductor and setup must be in preferred balance or resonance with the circuit of the power supply, or the transfer of energy from the power supply to the inductor and workpiece will not be consumated. Thus, when a multiple-turn inductor is substituted for a single-turn inductor, or any other major variable of the work-load circuit is changed, some readjustment usually must be made in the power supply circuit to compensate for the resulting change in impedance. Depending on the type of power supply employed, matching transformers or variable capacitors are commonly used for this purpose. However, it should be recognized that with any power supply the ability to match impedance is limited; inductor design and work load are thereby affected.

Quantity Limitations. Although induction heating equipment is relatively expensive, and although most induction brazing setups (inductors and fixtures) are designed for one assembly only, the induction brazing process is not limited to mass repetitive production. Because most inductors are simple and inexpensive to construct and many brazing fixtures are neither elaborate nor expensive, the process is also well suited for handling small quantities of assemblies in a variety of shapes and sizes. Also, because the same induction heating machines are often capable of performing a variety of heat treating operations, induction brazing has been widely adopted by both jobbing shops and captive plants that perform both brazing and heat treating. For high-volume production of assemblies of relatively few designs, the compactness of induction brazing equipment enables a plant with limited space to set up for induction brazing.

Automation. When production quantities warrant the investment, the induction brazing setup can be partly or fully automated.

Brazing Combined With Heat Treating. Because the temperatures used in induction brazing are frequently close to those used in heat treating, the two operations can often be performed simultaneously or in sequence (see Examples 589 and 591). In some applications, significant cost savings can be realized by brazing, austenitizing for hardening, quenching (usually with a spray) and tempering in an automated sequence of operations.

Principles of Operation

In induction brazing, the distribution of heat to sections of the joint depends largely on the contour of the inductor and the proximity of the inductor to the surfaces to be heated. The rate of heating varies inversely with the distance between the inductor and the workpiece surface. This relationship is not linear; the heating rate drops very rapidly as the distance is increased. Increasing the distance between the inductor and the joint reduces the thermal gradient across the joint but, at the same time, rapidly reduces heating efficiency. At some distance from the inductor, coupling between the inductor and workpiece is broken, and all heating ceases.

Apart from the inductor and the energy transmitted by it to the workpiece, the heating of a metal by induction for any purpose is also influenced by the mass, electrical resistivity and magnetic permeability of the metal. Under identical conditions, a thin section will heat to a given temperature faster than will a thick section, a metal with high electrical resistivity will heat faster than one with low resistivity, and magnetic metals will heat faster than nonmagnetic metals.

Brazing of Steel. Carbon and low-alloy steels and ferritic and martensitic (400 series) stainless steels are magnetic and have comparatively high electrical resistivity; therefore, they will heat very rapidly with less power input than would be required for heating a nonmagnetic, low-resistivity metal such as copper. Hysteresis losses play a minor role in the heating of magnetic metals; rapid heating is primarily the result of high electrical resistivity and magnetic linkages.

When brazing steel to steel, differences in the mass of the components are often significant. Much more energy must be introduced into the heavier component than into the lighter component to achieve a similar temperature rise in each. If the mass of one component is very much greater than that of the other, it may be advisable to generate all of the heat energy in the heavy component and to allow the light component to heat solely or largely by thermal conduction.

Brazing of Steel to Copper. In brazing steel to copper, the steel will heat much more rapidly than the copper unless provision is made to equalize the heating rates. In practice, this is accomplished by coupling the inductor more closely to the copper than to the steel or by adding more turns to that portion of the inductor heating the copper. Similar provision must be made in brazing steel to brass or to austenitic (nonmagnetic) stainless steel. Steel will heat much faster than either of these metals, although the differential in heating rates is less than that for steel and copper.

Power Supply

Induction brazing is usually done at frequencies of 10 kHz and higher. A variety of types of commercial power supplies are available, ranging in rating from about ½ kilowatt to several hundred kilowatts, thus providing a wide selection that can be used for single or multiple inductors.

1010 steel brazed to nickel; silver alloy filler metal (BAg-1)

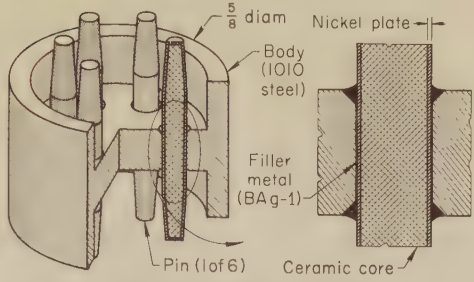


Fig. 1. Electrical coupling in which nickel-plated ceramic pins were induction brazed to a steel body

Motor-generator units are available with power-output ratings from 5 to 500 kw or more and operating frequencies of 960 Hz to about 10 kHz. A typical motor-generator unit consists of a high-frequency generator driven by a motor, capacitors connected across the output terminals to offer a high power factor, a transformer between inductor and generator with a turn ratio to match a desired work-load impedance, and electrical controls such as voltage regulators, switches, meters, and automatic timers.

Most motor-generators are used with a 60-Hz power input and are designed to deliver full power at a particular voltage, current, and power factor. In order to transfer power from the generator to the workpiece, the generating source must be matched to the work load, a function that is performed by the matching transformer and, when required, by altering the turns of the inductor or work coil.

Solid-State Power Supplies. Solid-state, high-frequency power supplies can be substituted for motor-generator units to provide power outputs of 50 kw or more at a maximum operating frequency of 10 kHz. Based on cost, these units are not competitive with the motor-generator at lower power.

The solid-state unit provides high-frequency power through the use of silicon controlled rectifiers, together with automatic power-factor control to compensate for changes that occur at the inductor when the resistivity of the work metal increases with increasing temperature or when a magnetic work metal passes the Curie point. The unit consists of a rectifier section, operating on 60-Hz alternating current and producing a substantially constant level of direct-current voltage, an inverter section producing variable-frequency alternating voltage, a series reactor, an output transformer, and power-factor corrective capacitors.

Vacuum-tube units are available with rated capacities ranging from ½ to 600 kw; output frequencies usually range from 180 to 450 kHz, although even higher frequencies are available. Vacuum-tube units are often referred to as "RF" or radio-frequency units.

Vacuum-tube units consist of a power-supply section and an oscillator section. The power-supply section provides the high voltage for the oscillator tube after rectification to a pulsating direct current, usually by mercury-vapor tubes. The oscillator tube and a tank circuit consisting of a matched inductor and capacitor comprise the oscillator section. The oscillator tube controls the amount of electrical energy delivered to the tank circuit, from which the energy is removed by the coupled load. A small and proportionate amount of the power in the tank circuit is fed back into the grid of the oscillator tube to control the current that is delivered to the tube, and the tube in turn controls the amount of electrical energy entering the tank circuit. The frequency developed in the converter is determined by the inductance of the tank coil and by the capacitor, which form a parallel tuned circuit. A load-matching network electrically coupled to the tank circuit is used to transmit tank-circuit energy to the work.

Selection of Frequency. Power for most induction brazing operations is supplied by high-frequency induction heating equipment, usually with operating frequencies of not less than 10 kHz. However, the range of suitable frequencies higher than 10 kHz is very broad and suggests that, in brazing, the factors of power input and matching impedance outweigh frequency in importance. In this respect, the heating requirements for induction brazing differ markedly from those of induction heating for surface hardening, which requires very high frequencies, or of billet heating, which is most efficient at lower frequencies.

Motor-generator units with frequencies of about 10 kHz and vacuum-tube units with frequencies as high as 460 kHz can be used for induction brazing.

In general, motor-generators are more efficient for heating large and heavy components at high power inputs, using inductors with similar impedance values and close coupling. Vacuum-tube units are generally more versatile, making it possible to process a wider variety of brazing and other heating applications with the same power supply. They often present fewer problems in matching impedances, and permit the use of inductors with close or loose coupling, or combinations of both in the same multiple-turn inductor, which is often advantageous in induction brazing of dissimilar metals. Vacuum-tube units also make it possible to combine brazing and thin-case hardening in a single operation.

For heating steel, the lower frequencies of the motor-generator can more often be tolerated than for heating copper, and may be desired. Because steel is only a fair conductor compared to copper, for the same power input, the surface heats faster and heat penetration is much slower.

Inductors

Among the many variables that affect the pattern of heating obtained by induction and that, therefore, are pertinent to induction brazing, are: (*a*) the shape of the inductor that produces the magnetic field, (*b*) the number of turns in the inductor, (*c*) the spacing between turns of the inductor,

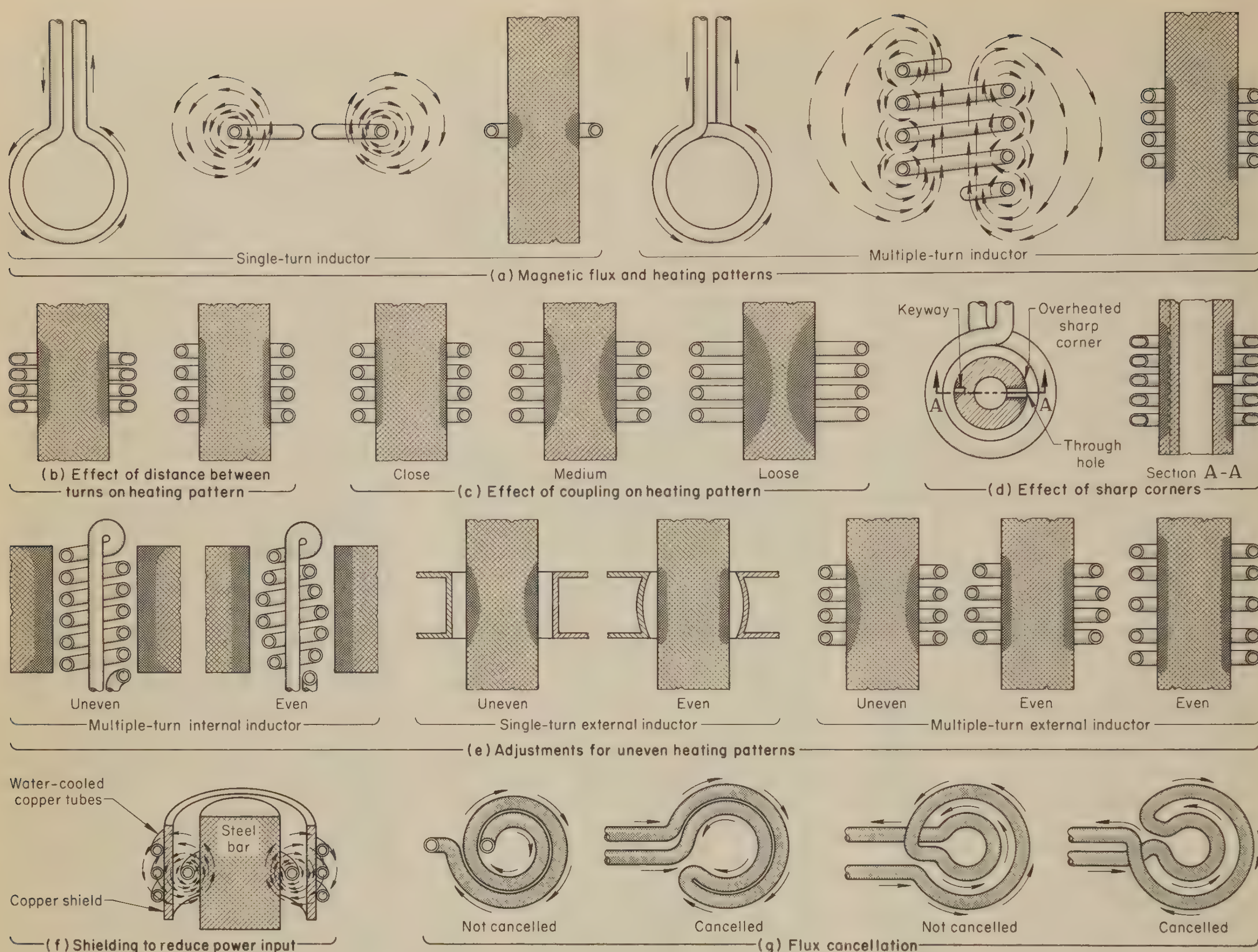


Fig. 2. Magnetic fields and heating patterns produced by various inductors

(*d*) the distance (air gap) between the turns of the inductor and the workpiece, (*e*) the presence of sharp corners on that portion of the workpiece within the magnetic field, (*f*) the presence of metallic shields within or near the inductor, (*g*) the operating frequency, and (*h*) the alternating-current power input.

Magnetic Fields and Heating Patterns. Examples of magnetic fields and heating patterns produced by induction are shown in Fig. 2. The patterns of magnetic flux for a single-turn and a multiple-turn inductor are shown in Fig. 2(a), along with the heating patterns developed by these inductors. The effect of inductor pitch, or the distance between turns in a multiple-turn inductor, on heating pattern is shown in Fig. 2(b); finer-pitch windings develop a deeper heat pattern than loose windings. The effect of coupling, or the air gap between inductor and workpiece, on heating pattern is shown in Fig. 2(c). The effect of sharp corners, such as those on a keyway, on the heating pattern developed in a multiple-turn inductor is shown in Fig. 2(d); the heat builds up excessively at sharp corners. Figure 2(e) shows modifications in heating pattern that result from modification of coil contour in a multiple-turn inductor designed for heating internally; contour of the inductor tube in a single-turn inductor; and coupling, coil contour and pitch in a multiple-turn inductor.

The use of an external copper shield to dissipate some of the power input of the inductor, and thereby to reduce heating rate and intensity, is illustrated in Fig. 2(f). This same principle was employed in Example 588 to achieve a similar purpose. Although use of a dissipator shield is rare, it is sometimes more effective than a change in coupling in the control of heat input. Finally, the development and cancellation of flux fields is shown schematically in Fig. 2(g). When the turns of an inductor are made to carry the current in the same direction, a flux field is developed, whereas when the turns are made to carry current in opposing directions, magnetic flux is cancelled. Generally, cancellation of the flux field should be carefully avoided; however, as demonstrated in Example 595, cancellation can sometimes serve a useful purpose.

Although, as shown in Fig. 2, heating patterns can be altered in many ways, the rate of heating obtained by induction will depend on the resistance of the work metal to the flow of current induced in it by the inductor. The flow of current will depend on the strength of the magnetic field to which the work metal is exposed.

Inductor Design for Brazing

The success of an induction brazing application depends greatly on the design of the inductor, which, in turn, must be related to the dimensions and configuration of the assembly to be brazed, the heat pattern desired, the heating time that will produce a minimum of work-metal discoloration and oxidation, and the amount of power available. The size of the production run also influences inductor design. A single multiple-turn inductor may suffice for brazing small to medium quantities of assemblies intermittently. A series-type inductor, consisting of two or more single-turn or multiple-turn inductors of identical design, will braze larger quantities of the same assembly intermittently, the increase in production rate usually depending on the number of individual inductors in the series. Finally, assemblies can be induction brazed continuously as they

are carried on a conveyor belt or turntable to hairpin or pancake-type inductors that permit entrance to, and exit from, the heating zone without obstruction.

For the most rapid heating rates, inductors are designed to provide the maximum flow of current in the inductor, and the closest permissible coupling between inductor and workpiece, after consideration of heat distribution, work-handling features, and high-voltage arcing between the turns of the inductor or between the inductor and the workpiece. In practice, considerable variation exists in the design of inductors for vacuum-tube and motor-generator sources of high-frequency power. For the range of frequencies suitable for induction brazing, however, the inductors are made of copper, because of its high electrical conductivity and wide availability at relatively low cost.

Basic Designs. A variety of basic designs of inductors for use primarily with vacuum-tube power supplies with or without matching transformers are shown in Fig. 3. Shown in Fig. 3(a) is a modified single-turn inductor capable of brazing two different joints simultaneously on a single assembly. Figures 3(b) through 3(e) show multiple-turn inductors that have been formed to different geometric shapes to accommodate the contours of specific assemblies. Two types of multiple-turn inductors that are widely used to braze tungsten carbide cutting tips to steel shanks are shown in Fig. 3(f) and 3(g). Unlike the preceding inductors, all of which were made from copper tubing, the inductor shown in Fig. 3(h) is machined from a solid copper bar into which holes have been drilled for water cooling. Two-station and four-station versions of the solid copper inductor are shown in Fig. 3(j) and 3(k).

The so-called "pancake" type of inductor represents a different design category. Double-pancake inductors, such as those shown in Fig. 3(m) and 3(n), are sometimes substituted for the multiple-turn inductors in Fig. 3(f) and 3(g) to braze carbide tips to steel tools. Assuming that both types of work coils are equally satisfactory for brazing, the selection of a pancake-type coil may be based on matching impedance. Because flat pancake inductors permit unobstructed passage of workpieces either above or below them, they are widely used for continuous brazing on conveyor belts (Fig. 3p) and turntables (Fig. 3q); a variety of asbestos products are suitable for conveyor belting and table-top coverings.

Another type of work coil used in induction brazing, especially in conveyor-type operations, is the "hairpin" inductor. Examples of hairpin inductors suitable for use with conveyor belts

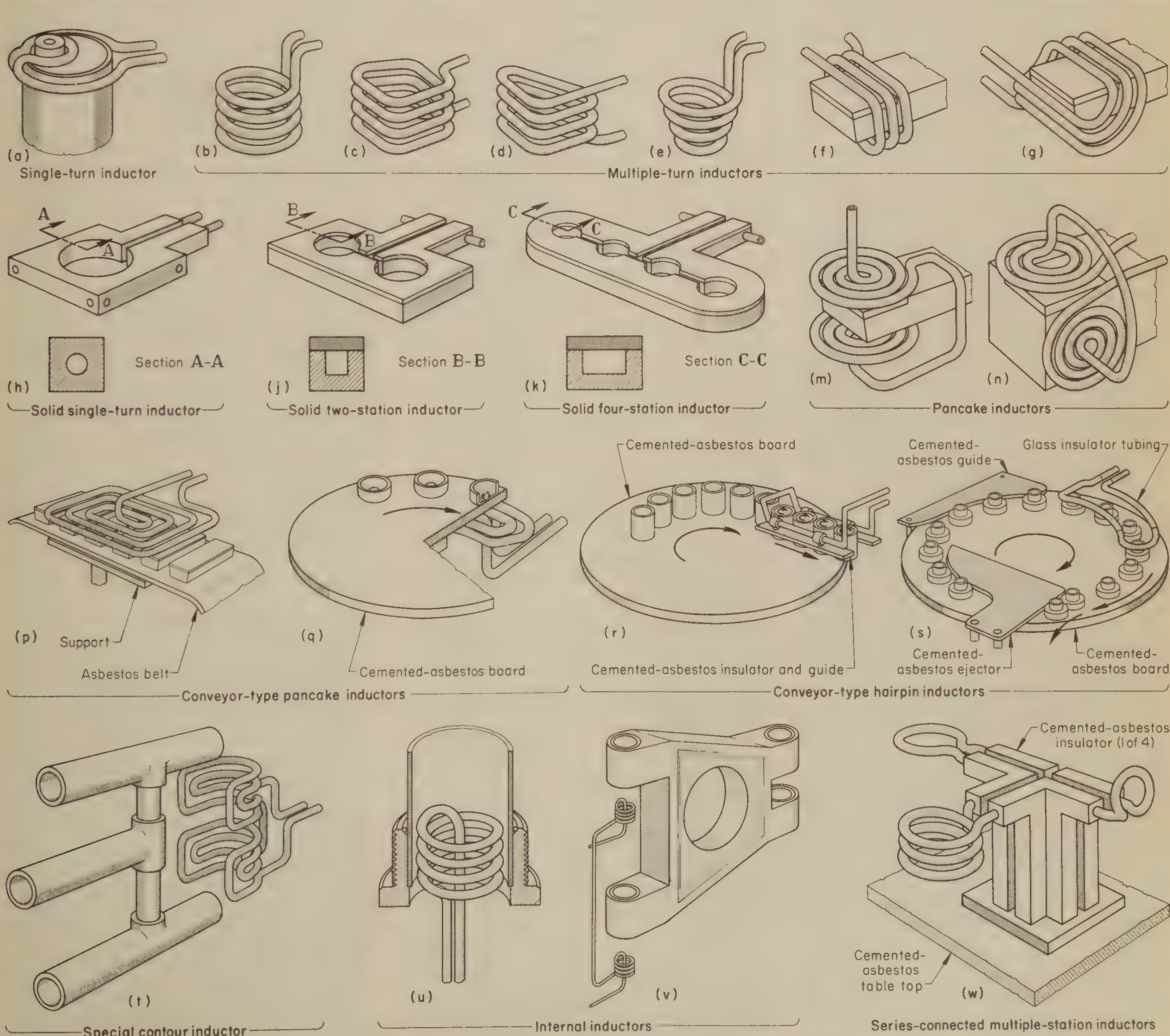


Fig. 3. Basic designs of inductors for use primarily with vacuum-tube power supplies

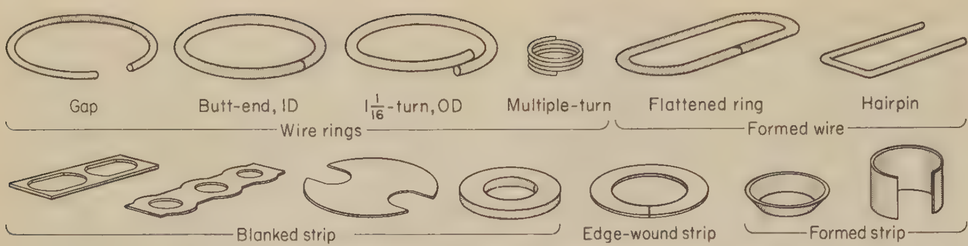


Fig. 4. Typical filler-metal preforms used in induction brazing

Table 1. Compositions, Solidus and Liquidus Temperatures, and Brazing Temperature Ranges for Filler Metals Commonly Used in Induction Brazing

AWS classification	Composition, %: Ag	Cu	Zn	Cd	Ni	Temperature, F: Solidus	Liquidus	Brazing
BAg-1	44 to 46	14 to 16	14 to 18	23 to 25	...	1125	1145	1145 to 1400
BAg-2	34 to 36	25 to 27	19 to 23	17 to 19	...	1125	1295	1295 to 1550
BAg-3	49 to 51	14.5 to 16.5	13.5 to 17.5	15 to 17	2.5 to 3.5	1170	1270	1270 to 1500

or turntables are shown in Fig. 3(r) and 3(s). Because the heating of steel in a hairpin inductor is often restricted to a very limited area, it is usually necessary to rotate the workpiece in order to expose all of the joint area that requires heating to the flux path of the inductor. Rotation is often achieved by forced frictional contact of the workpiece with a stationary guide as it is being conveyed forward in a horizontal plane.

The inductor shown in Fig. 3(t) is typical of a class of rather elaborately contoured work coils that require considerable ingenuity to design and fabricate. This inductor is essentially a double pancake, with each pancake formed to a U-shape contour. The coil surrounds a sufficient area of the joints to ensure uniform heating by induction and conduction. If more time is required to allow for conduction of heat to certain remote areas of the joints, a pulse heating technique (power on, power off, power on) can be employed to ensure uniform heating.

Although inductors designed for heating internally are relatively inefficient in terms of power input to the work load, they are useful in brazing dissimilar metals and in special applications where the use of an external inductor is not feasible. A typical work coil for heating internally is shown in Fig. 3(u). The application requires brazing a portion of the external surface of a hollow copper tube to the internal surface of an externally threaded steel bushing. Heating the assembly with an external inductor would severely overheat the threads unless coupling was loose. With loose coupling, heating would be slow and the copper would heat last, thus jeopardizing the soundness of the brazed joint. In contrast, heating internally favors heating of the copper, so that both copper and steel can be brought to brazing temperature at about the same time. A two-coil internal inductor for brazing two bushings in a hinge simultaneously is shown in Fig. 3(v).

A setup for series-connected, multiple-station inductors linked to a common vacuum-tube power supply and matching transformer is shown in Fig. 3(w). Such a setup is well suited for manual brazing operations involving two or more operators. The inductors can be energized continuously to serve as a common power source for use by the operators, as required. Inductors can be readily disconnected and replaced to accommodate a variety of different assemblies.

Tubing for Inductors. Most inductors are made of commercial copper tubing. The size of the tubing selected for a specific inductor must be large enough to accommodate the current input and to permit an adequate flow of water for cooling. With machines of low power, the tubing may be only $\frac{1}{8}$ in. in diameter, but for units of 20 to 50 kw, it is usually $\frac{3}{16}$ or $\frac{1}{4}$ in. in diameter. (There is available, however, $\frac{1}{8}$-in.-OD tubing with a wall thickness of only 0.018 in. that may be used in the 25 to 50-kw range provided that the flow of pressurized cooling water is adequate.)

Inductors for frequencies obtained from motor-generator units (up to 10 kHz) are generally of two basic designs: (*a*) a single-turn coil, for high current densities (20 to 50 times the generator output current), which is employed to confine heating to a comparatively narrow band or segment; and (*b*) a multiple-turn coil for low current densities (1 to 5 times the generator output current), which is employed to heat a wider or larger area. A step-down transformer is ordinarily utilized between single-turn inductors and the generator; multiple-turn inductors are connected to the generator either directly, or indirectly through a step-down transformer.

The wall thickness of the copper conductor used with motor-generator units is important. For efficient operation at various frequencies, the following minimum wall thicknesses may be used as a guide in constructing multiple-turn coils:

Frequency, kHz	Minimum wall thickness, in.
1	0.120
3	0.070
10	0.040

In the construction of single-turn coils, with which current density may be considerably higher, the values of minimum wall thicknesses listed above should, whenever possible, be multiplied by a factor of three or four.

Cooling. Single-turn and multiple-turn inductors may be formed from tubing or a combination of tubing and solid bus bar. Because of the high current density and the extremely thin cross section in which the current confines itself, water cooling is required. This is accomplished by circulating water through the tubes or through channels provided in the bus bar for that purpose. These channels may be made by drilling connecting holes or milling out a path to make a complete loop around the bore of the inductor, and then plugging the exposed ends of the holes or brazing a copper sheet over the milled passage to make a continuous watertight cooling channel. Cooling passages with cross-sectional areas of 0.050 to 0.125 sq in. will provide adequate cooling at water pressures of 40 to 50 psi for power inputs of 30 to 150 kw.

Water used for cooling should have a hardness of less than 12 grains per gallon. If the water-cooling passages are small in relation to the current load carried by the inductor, it may be necessary to use distilled or deionized water to avoid a buildup of deposits that could eventually stop circulation. Preferably, the water should be filtered to remove foreign particles that might clog small passageways, especially when inductors of intricate design are being used. The water should have an inlet temperature above 70 F and below 95 F, and flow should be sufficient to prevent the outlet temperature from rising above 150 F.

Coupling and Spacing. For efficient transfer of energy, the inductor bore may be $\frac{1}{8}$ to $\frac{1}{4}$ in. larger in diameter than the workpiece — resulting in an air gap, or coupling, of $\frac{1}{16}$ to $\frac{1}{8}$ in. between the inductor and the workpiece. As the bore of the inductor is increased, the workpiece is subjected to a weaker portion of the magnetic field, heating time will be increased, and the heating pattern will be deeper, unless the power density is increased correspondingly. Although loose coupling is seldom desirable for induction hardening, it is often employed in brazing to provide more uniform heating and to avoid overheating the surface.

Inductor coil turns are normally spaced $\frac{1}{16}$ to $\frac{3}{32}$ in. apart. Considerable variation in the heat pattern can be obtained by adjustment of either the spacing between turns or the dimension of the air gap for individual turns.

Filler Metals

Requirements of a filler metal for induction brazing are:

1. Melting temperature lower than temperatures at which the metals being brazed are adversely affected
2. Ability to wet the metals being brazed
3. Narrow melting range (difference between solidus and liquidus temperatures)
4. Sufficient fluidity at the brazing temperature to enable it to flow rapidly through the joint by capillary action
5. Composition chemically compatible with the base metal
6. Ability to form joints that have the required mechanical properties.

Most of these requirements also apply, to varying degrees, in many torch and furnace brazing operations, but a narrow melting range is especially important in induction brazing operations. Filler metals with wide melting ranges flow more sluggishly and are more susceptible to liquation than are alloys with narrow melting ranges. Fast flow is particularly desira-

ble in induction brazing, because time cycles for this process are short.

Selection of Alloy. Compositions, solidus and liquidus temperatures, and brazing temperature ranges for the three silver alloys that are most widely used as filler metals in induction brazing of steel are given in Table 1. Of the three alloys, BAg-1 is used much more extensively than the other two alloys, for two main reasons. First, the brazing temperature range of BAg-1 is the lowest of the three. (A low-temperature brazing range is desirable because the workpiece is normally heated in air, and the lower the brazing temperature, the less will be the oxidation of the workpiece.) Second, the melting range of BAg-1 is only 20 F, making it the most free-flowing of the three alloys. BAg-1 is recommended for brazing steel to steel and is also suitable for brazing steel to copper alloys.

BAg-2 melts at a higher temperature than BAg-1 and has a wider melting range, which makes it less suitable for general-purpose use. However, this property makes BAg-2 more suitable than BAg-1 for large-clearance joints.

BAg-3 is often preferred for joining carbide tips or inserts to steel, because it has good wetting action on carbide (see Example 590). Also this filler metal is preferred for joining stainless steel to itself (as in Example 595), or to carbon steel.

Selection of Form. The filler metals listed in Table 1 may be purchased as spools of wire of various diameters and as strips of various thicknesses, which can be made into preformed shapes if desired. Filler metal is also available in powder form.

Joint design, method of assembly, and cost are the main factors that govern the choice among these forms. Preforms are usually preferred because they can be used with minimum waste and lend themselves to preplacement in or around joints of various designs. Preforms of almost any shape can be made from strip with a simple punch and die or from wire by forming. Some typical preforms are shown in Fig. 4.

Rings often serve as preforms. They can be made by winding wire on an arbor and then slitting the springlike coil lengthwise to produce the rings. Some experimentation is often needed to determine the arbor diameter that will produce rings of the correct diameter after springback.

Many standard types and sizes of rings (and washers) also are commercially available. The sizes are commonly specified by their inside diameters, the rings being meant to fit around joints. The butt-end ring shown in Fig. 4 is of a design that allows for expansion during preplacement. The 1$\frac{1}{16}$-turn ring (see Fig. 4) is designed to allow compression during preplacement inside a joint, and it is specified by its outside diameter.

For some joints, preforms made from strip are more suitable than shapes formed from wire. When large numbers of blanked or formed preforms are needed, their cost may be reduced by buying them from a metal producer, who can reprocess the waste punchings, whereas a user must sell the waste as scrap.

Filler metal in powder form is often used, although if it is used on the exterior of the joint some provision must be made to hold it in place. One method is first to brush the joint with paste flux and then to dust the filler-metal powder lightly onto the flux while it is still wet. Another method is to mix the powder with flux and a binder to form a paste, which is then applied by brushing.

Fluxes

Flux is required for induction brazing. The flux used should decompose oxides without corroding the base metal or the filler metal, should be extremely active because of the short brazing times employed, and should be easy to remove after brazing.

Flux of type 3A (see Table 2, page 628, this volume) meets these requirements and is used for an estimated 95% of the induction brazing applications that involve steel. This flux is composed of a mixture of a wetting agent and one or more of the following materials: boric acid, borates, fluorides and fluoborates, and is effective within the temperature range of 1050 to 1600 F. It is available in the form of paste or powder, and can be mixed to a liquid consistency with water, alcohol or monochlorobenzene.

Paste and liquid fluxes are most often applied to the joint by brushing. When more convenient, flux powder can be sprinkled on or in the joint, or liquid flux can be sprayed.

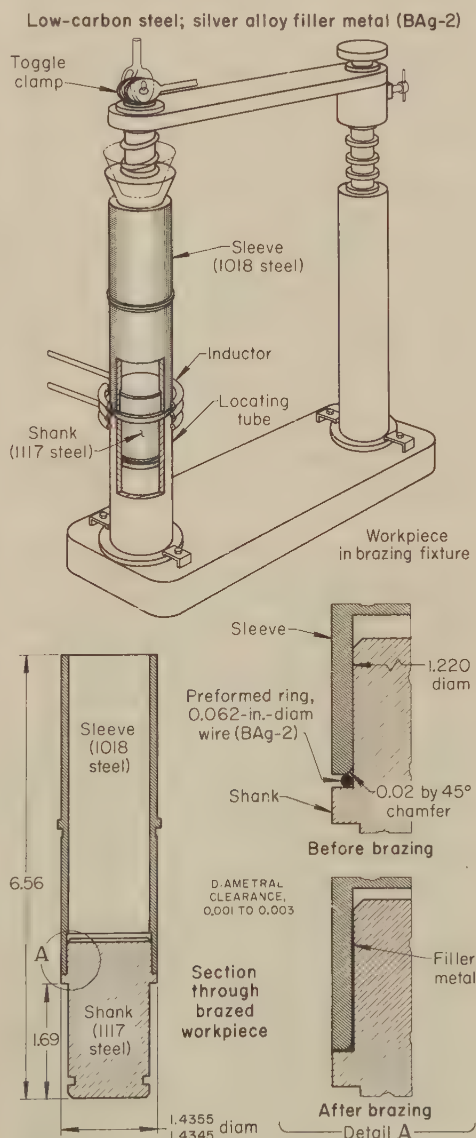


Fig. 5. Induction brazed drive spindle positioned in the inductor by a fixture that finished assembling the components by forcing them together during brazing (Example 587)

Assembly

Methods of preparing joints and assembling the components are generally the same as are used prior to furnace brazing (see the article on Furnace Brazing, which begins on page 593).

The recommended diametral clearance for joints brazed with the filler metals listed in Table 1 is generally 0.002 to 0.005 in. However, based on experience with similar joints, a clearance less or greater than the recommended value is often selected for a specific joint. If the distance the filler metal travels while filling the joint is greater than normal, the clearance (or the brazing temperature, or both) may have to be increased.

Fixturing

Most assemblies that are brazed by induction require some fixturing, even though the components may be held securely together mechanically before being positioned in the inductor. Fixtures can range from a simple locating pin to hold the assembly in the center of the inductor, to an elaborate clamping and holding arrangement. Every assembly must be considered separately in relation to its fixturing requirements. Fixture design is influenced not only by the size and shape of the assembly, but also by the rate at which assemblies are to be produced.

Functions of a fixture may include supporting the assembly, positioning the assembly in the inductor, and holding the assembly securely together during the brazing cycle until the filler metal has solidified.

Sometimes a fixture is designed to perform the additional duty of assembling the components during the brazing cycle, as in the next example.

Example 587. Use of a Fixture That Held an Assembly in the Inductor and Also Forced the Components Together During Brazing (Fig. 5)

An induction brazed drive spindle, consisting of an 1117 steel shank and a 1018 steel sleeve (see perspective in Fig. 5), had originally been completely assembled by hand and supported in the inductor by only a tubular steel locating fixture clamped to a baseplate. For brazing by this method, the joint had a diametral clearance of 0.001 to 0.004 in., the 45° chamfer on the inside diameter of the sleeve was 0.04 in. wide, and the filler metal was a hand-formed ring of 0.062-in.-diam BAg-1 wire. The assembly was brazed at approximately 1350 to 1450 F, using high-frequency (400 kHz) current supplied by a 4-kw vacuum-tube unit.

To increase the production rate and to effect savings in production costs, the fixture was altered to incorporate the spring-

loaded locating cone shown in perspective in Fig. 5. With this arrangement, the assembly was placed in the locating tube with the shank down. The sleeve was centered and held in place by the locating cone, which was forced against the sleeve by the toggle clamp and spring. Before brazing began, the two components of the assembly were held apart by the filler-metal wire (see detail A in Fig. 5). As the assembly was heated and the filler metal melted, the spring-loaded cone pushed the sleeve and shank together, forcing liquid filler metal in two directions to fill the joint.

For brazing with the improved fixture, the maximum diametral clearance of the joint was reduced from 0.004 to 0.003 in., and the chamfer on the sleeve was reduced to 0.02 in. The filler metal was changed to a preformed ring of BAg-2, which has a freezing range 150 F wider than that of BAg-1. Brazing was done at 1300 to 1325 F (the time to reach this temperature range was determined, and the automatic brazing cycle was set accordingly), using the same power supply and frequency as originally. The method was completely successful and the assemblies produced were free from distortion.

The sequence of operations by the improved method was:

1. Clean parts in alcohol.
2. Coat joint with type 3A flux.
3. Place preformed filler-metal ring on shank.
4. Assemble parts in spring-loaded fixture and clamp.
5. Braze at 1300 to 1325 F for 5 to 15 sec, depending on diameter of part (automatic timing); cool in fixture for 5 to 10 sec.
6. Remove assembly, rinse in water at 180 F for 5 min (or place in warm water and hand-brush flux); blow dry.
7. Dip in a rust preventive.

Using the improved method, production time was reduced by 30% and the time needed to straighten assemblies brazed by the original method was eliminated.

Selection of materials for fixtures is especially important. If all components of a fixture are sufficiently remote from the inductor (several inches away) to be unaffected by its magnetic field, materials used for fixtures for other brazing processes are suitable. However, if all or part of a fixture is within about 2 in. from the inductor or the leads to the inductor, the fixture must be made of a nonmetallic, and preferably heat-resisting, material. Several such materials are commercially available; one of the most common is cemented-asbestos board. This material can be machined to various shapes, is electrically nonconductive, nonflammable, and withstands heat. It is supplied in sheets ranging in thickness from ⅛ to 2 in. Other suitable nonmetallic materials include heat-resisting glass, ceramics, quartz and plaster. When use of a metal near the inductor or the leads is unavoidable, aluminum, copper and brass are the preferred metals.

Brazing of Tight Joints

For joints brazed with the high-silver alloys, the recommended diametral clearance (positive allowance) is 0.002 to 0.005 in. However, in some applications this much clearance results in an unacceptable amount of eccentricity in the brazed assembly. A common method of eliminating this in most joints is to use a clearance range of 0.001 to 0.003 in.; with an active, free-flowing filler metal such as BAg-1, acceptable joint penetration can usually be obtained. For some joints, even a diametral clearance of 0.001 to 0.003 in.

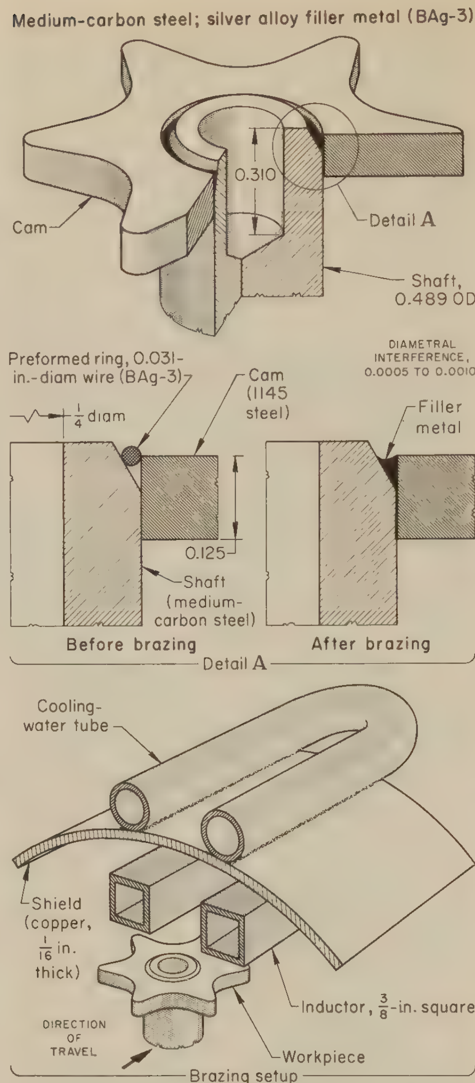


Fig. 6. Induction brazed cam and shaft that had to be assembled with a press fit to maintain concentricity (Example 588)

is unacceptable because of the resulting eccentricity, and a press fit is therefore necessary. Under these conditions, special provisions must be made, as in the example that follows.

Example 588. Induction Brazing With an Interference-Fit Joint (Fig. 6)

Three requirements for the medium-carbon steel cam-and-shaft assembly shown in Fig. 6 demanded special consideration in brazing: (*a*) the specified concentricity necessitated an interference fit of the joint at room temperature, (*b*) the hardness of the bearing area of the shaft had to be retained, and (*c*) the production requirement was 2400 brazed assemblies per hour.

The cam and shaft were assembled with a press fit (slight interference) to ensure concentricity; the end of the shaft was chamfered slightly to facilitate assembly and to form a V-groove for a preformed ring of BAg-3 filler metal (see Fig. 6).

During development of the technique for making the joint, it was found that an excessive amount of heat was being conducted away from the joint area and was resulting in too long a heating time and softening of the bearing area of the shaft. This difficulty was overcome by machining a cup-shape recess in the end of the shaft, as shown in Fig. 6, by employing vacuum-tube power supply units with a frequency of 450 kHz, and by using flat inductors that faced the V-groove.

The production requirement of 2400 assemblies per hour was met by the use of two 25-kw machines, each with two inductors. The assemblies were dipped in liquid type 3A flux and manually placed in holding fixtures mounted on a conveyor traveling at 30 ipm. Preformed 370° rings, 0.480-in. OD and made from 0.031-in.-diam wire, were dropped in place in the grooves.

The assemblies passed under a 36-in.-long inductor that preheated the joint area and dried the flux, and then under a 30-in.-long inductor where brazing was completed. The rate of heating by the inductors was controlled by adjusting the air gap between the inductor and the workpiece. The preheat inductor was inclined to give decreasing air gap; the brazing inductor was horizontal, giving a constant air gap. A water-cooled dissipator shield above the brazing inductor de-intensified the flux field to help reduce the heating rate to the desired level.

After brazing, the heated portion of the assemblies cooled in air to about 800 F during the next 120 in. of conveyor travel and were then sprayed with water during the following 20 in. of travel to remove flux and further cool the assemblies. The assemblies were then ejected automatically from the holding fixtures.

Simultaneous Brazing and Hardening

The use of induction brazing is generally precluded for joining steels if the brazed assembly must be subsequently heat treated at a temperature above the melting temperature of the filler metal, because this would destroy the brazed joints. However, this potential disadvantage of induction brazing can often be overcome by brazing and heat treating in a single operation.

Therefore, in the planning of brazing and heat treating operations, consideration should always be given to the possibility of combining the two operations, or of using the induction equipment for heat treating local areas on the workpiece in a separate induction heating operation (see Example 591).

The example that follows describes a typical application in which brazing and heating prior to quenching were performed simultaneously.

Example 589. Brazing and Surface Hardening in One Operation (Fig. 7)

Originally, the valve-and-tube assembly shown in Fig. 7, which was used in grease-pumping equipment, was furnace brazed with BCu-1 filler metal. The tube was made of 1010 steel and the valve of 1040 steel. The valve face was subsequently hardened by induction heating and water quenching. (Quenching the entire assembly after furnace brazing was unacceptable because it produced distortion.) Furnace brazing, which was subcontracted because the manufacturer did not have suitable equipment, resulted in difficulties. First, the valves did not harden correctly, because they had been decarburized in the brazing furnace atmosphere. In addition, shipping to and from the vendor disrupted plant schedules. The cost of furnace brazing (filler metal, labor, overhead and profit) was $0.1000 per assembly; the cost of induction hardening, $0.1385 per assembly, for a total cost of $0.2385 per assembly. To eliminate these problems, processing was changed to in-plant induction brazing performed simultaneously with heating for quenching, as described below.

Filler metal was 0.040-in.-diam BAg-1 wire formed into 9/16-in.-ID rings. (The use of rings of different size than the part on which they are to be placed, so that they spring into place, is common practice.) A

groove was machined in the valve, as shown in Fig. 7, to make a pocket for the preformed ring. Assembled in this manner, the filler-metal ring just reached the brazing temperature of 1145 to 1250 F when the valve face reached the hardening temperature of 1450 F, because of the characteristic steep gradient caused by the rapid heating. (Had the filler metal reached the hardening temperature, it would have been excessively oxidized.)

A press-fit joint had been employed when BCu-1 filler metal was used with furnace brazing. On changing to BAg-1 filler metal and induction brazing, the diametral clearance between the two components was established at 0.004 to 0.008 in. In practice, clearance was consistently in the middle of this range.

The inductor was made from 3/16-in.-OD copper tubing and had two turns on a 1-in. diameter. The brazing fixture comprised a holder for the tube and a quench ring of low-carbon steel tubing, which surrounded the inductor with a ½-in. clearance to avoid induction heating of the quench ring. The spray of tap water from the quench ring was directed at the face of the valve.

Timing for the brazing cycle was determined visually as follows: An assembly was placed in the machine and the inductor energized. When the operator saw the filler metal emerge and form a slight fillet at the edge of the joint, he noted the time interval, shut off the power, and opened the quench-water valve. After the heating time was established, it was controlled by a timer, but the operator continued to operate the quench-water valve manually.

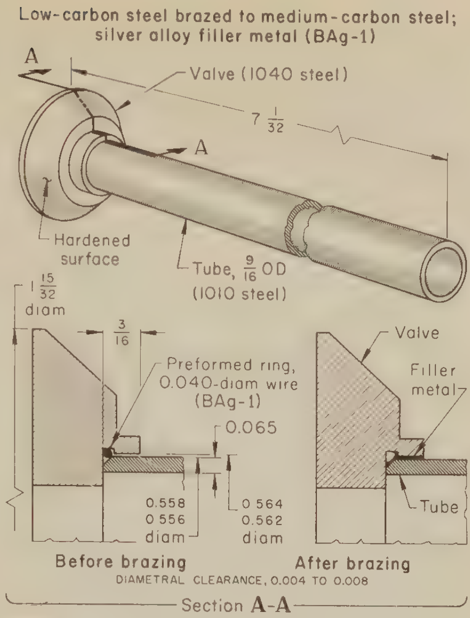
The sequence of operations was:

1 Degrease tube and valve.
2 Place preformed ring of filler-metal wire in groove.
3 Flux mating surfaces of tube and valve with type 3A flux.
4 Assemble components, and place assembly in fixture.
5 Heat for 30 sec.
6 Spray quench.
7 Remove from fixture.

After brazing and hardening, the assemblies were washed and pickled to remove flux. Then they were tempered for 1 hr at 375 F to obtain the required minimum hardness of Rockwell C 48 on the valve face. Other inspection requirements were a strong joint and squareness of the top of the valve with the tube (to ensure correct final grinding).

Production rate was 80 assemblies per hour; annual production was only 1200 assemblies, too small a number to warrant mechanization. The cost of the induction brazing machine, which was used also on other projects, was $11,000. Labor cost per assembly was $0.0396, overhead was computed at 350% of labor cost, cost of flux and filler metal was $0.0420, for a total cost of $0.2202 — compared with $0.2385 per assembly for furnace brazing and subsequent induction hardening.

Several years of field experience demonstrated the reliability of the simultaneous operation; failures were zero. Additional process details for simultaneous induction brazing and hardening are given in the table with Fig. 7.



Power supply	25-kw vacuum-tube unit
Frequency	400 kHz
Filler metal	0.040-in. wire, BAg-1
Flux	AWS type 3A
Heating temperature (valve face)	1450 F
Heating time	30 sec
Postbraze heat treatment	375 F for 1 hr
Production rate	80 assemblies per hour
Total cost per assembly	$0.2202

Fig. 7. Pump valve-and-tube assembly that was induction brazed and surface hardened in one operation (Example 589)

Brazing of Dissimilar Metals

In addition to the differences in characteristics of dissimilar base metals that affect their brazeability by any process — namely, differences in thermal expansion, thermal conductivity, and compatibility with specific filler metals — differences in magnetic characteristics also have an effect in induction brazing.

Despite the above variables, induction brazing is used successfully for joining a number of other base metals to steel. There are at least two methods for dealing with the difference in heating rates. One is to design the assembly so that the component that is heated more easily has the larger mass, which acts as the larger heat sink and reduces the heating rate. Another method is to design the inductor so that the component that heats more easily is positioned in a weaker part of the magnetic field.

Sometimes, when other base metals are to be brazed to steel, a compromise must be made in selection of filler metal. For instance, BAg-1 is generally preferred for brazing one ferritic steel to another, but when austenitic stainless steel is one of the base metals, BAg-3 is a better choice, because it is suitable for both base metals.

Difference in coefficient of thermal expansion (and contraction) of the base metals will produce shear stress in the cooling joint. This stress must sometimes be accommodated to avoid cracking of the joint. Accommodation can be provided by placing a relatively thick, ductile metallic interlayer between the base metals, such as that obtained with a sandwich consisting of a fine, iron gauze between strips of filler metal. Another method is to use a ductile copper strip clad on both sides with filler metal, as in the example that follows.

Example 590. Use of a Filler-Metal "Sandwich" To Avoid Cracking of a Brazed Carbide-to-Steel Joint (Fig. 8)

To avoid cracking of brazed joints between tungsten carbide tips and tool shanks of low-carbon steel or tool steel, a "sandwich" brazing technique was used. Brazing was done with a 10-kHz, 25-kw machine. The assembly rested on a cemented-asbestos board through which the inductor penetrated, as shown in Fig. 8.

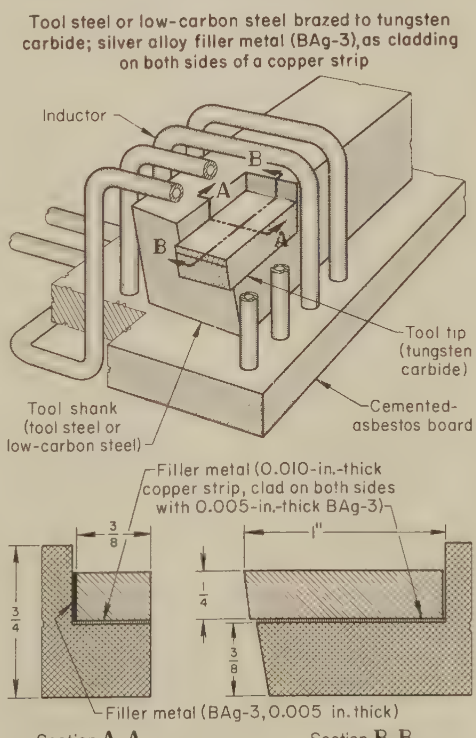


Fig. 8. Induction brazing of a carbide tip to a steel tool shank, using a filler-metal "sandwich" to prevent shear-stress cracking of the carbide (Example 590)

Those surfaces of the carbide tip to be brazed were prepared by grinding and those of the steel shank by machining and vapor degreasing.

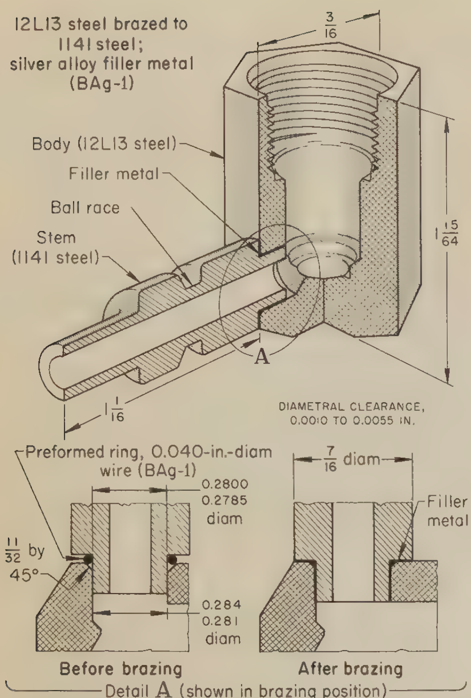
Filler metal for the portion of the joint between the bottom of the tip and the recess in the shank was a "sandwich" of 0.010-in.-thick copper strip, clad on both sides with 0.005 in. of BAg-3; filler metal for the vertical portion of the joint was a 0.005-in.-thick strip of BAg-3 (Fig. 8). The tip and shank were coated with flux and then assembled so that the tip rested on the filler-metal sandwich and also held the strip of solid filler metal against the sidewall of the recess.

The tip end of the assembly was inserted into the inductor only as far as the base of the tip to minimize the effect of the heat of brazing on the main portion of the shank. When the filler metal was melted, the tip was moved back and forth with a nonmetallic rod to puddle the filler metal, release gas bubbles and ensure good wetting. After brazing, the assembly was removed from the inductor, allowed to cool in still air, and then cleaned of flux.

The coefficients of thermal expansion of carbide and steel are different, causing the tip and shank to expand or shrink different amounts during heating to and cooling from the brazing temperature, which in turn produces a shear stress along the joint, sometimes large enough to crack it. The advantage of having the filler-metal sandwich beneath the tip was that the ductile copper yielded under the shear stress, allowing all components of the joint to remain firmly bonded.

Cost of Induction Brazements vs Forgings and Castings

If a part, ready for brazing, can be produced in an automatic bar machine, the brazed assembly will cost less than a similar part machined from a forging or a casting, provided that production quantities are sufficient to justify the cost of equipment for induction brazing. Hydraulic-actuator components,



Comparison of Direct Labor Costs

Forging	$0.040
Machining the forging	0.300
Total cost per fitting	$0.340
Machining two components before brazing	$0.160
Brazing	0.024
Total cost per fitting	$0.184
Saving per fitting by use of brazing	$0.156

Conditions for Induction Brazing

Power supply	25-kw vacuum-tube unit
Frequency	400 kHz
Filler metal	0.040-in. wire, BAg-1
Flux	AWS type 3A
Brazing temperature	1300 F, approx
Heating time	60 sec
Postbraze treatment	Induction harden race
Production with 6 inductors	125 fittings per hour
Annual production	36,000 fittings

Fig. 9. High-pressure fitting made as a brazed assembly of machined components instead of as a machined one-piece forging, to reduce cost (Example 591)

connectors, and pressure-line hardware are among the parts produced in automatic bar machines and assembled by induction brazing.

The example that follows describes an application in which cost was reduced by changing from a machined forging to a brazed assembly.

Example 591. Change From Forging to Induction Brazing That Reduced Labor Cost by 46% (Fig. 9)

Originally, the high-pressure fitting shown in Fig. 9 was made from 1117 steel by forging, machining, and carbonitriding all over (even though hardness was required only on the ball race). Direct labor cost for forging and machining was $0.34 per fitting.

Because the annual production requirement was 36,000 fittings, a lower-cost method was sought. The method was changed to the brazing together of a stem and a body produced in an automatic bar machine. The stem was made from 1141 steel because the ball race had to be hardened to Rockwell C 47 to 58 in a separate operation. The body of the fitting was made from 12L13 steel for ease of machining.

With the use of six inductors, supplied with power from a vacuum-tube unit and mounted on an insulated arm that could be swung over the assembled components, six assemblies were brazed simultaneously. Each inductor was a two-turn coil of 3/16-in.-OD copper tubing on a 1-in. diameter.

The components to be brazed were degreased, and then were assembled with a preformed ring of BAg-1 filler metal preplaced on the neck of each stem (Fig. 9). The preformed ring was located by a chamfer on the hole in the body. The diametral clearance in the joint was 0.0010 to 0.0055 in. After assembly, the joint surfaces, which were held apart by the filler-metal ring, were brushed with type 3A flux.

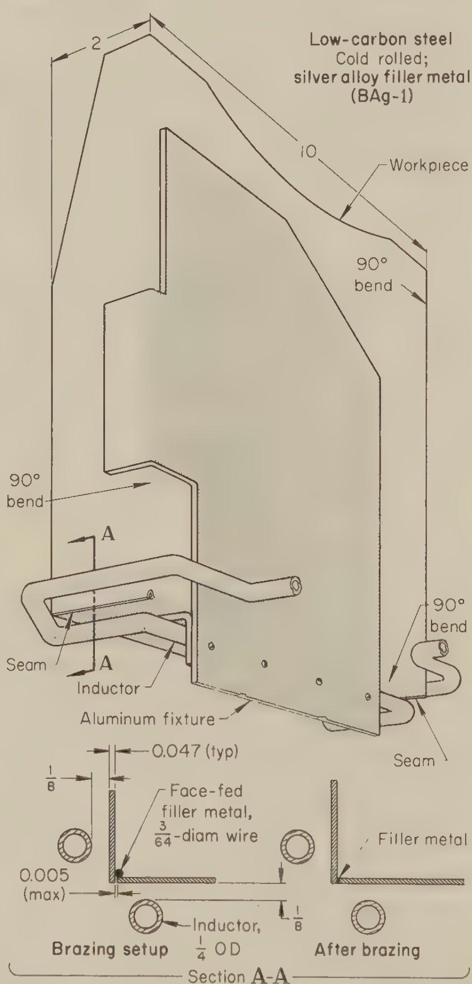
The assembly was placed in a positioning fixture, with the stem up. The inductor heated the assembly in 60 sec to approximately 1300 F. When the operator saw the filler metal emerge at the edge of the joint, he pressed each stem down firmly to seat it in the hole and to ensure that it was aligned and square. The assembly was allowed to cool in the positioning fixture until the filler metal solidified (approximately 1000 F). The brazed assembly was then removed with pliers and placed in a basket, for cooling to room temperature. Flux was removed by pickling and tumbling.

The races were subsequently heated to approximately 1500 F, by use of the induction brazing unit, and oil quenched. Heating in this operation was localized to prevent deformation at the brazed joint.

Cost of direct labor for machining and brazing was $0.184 compared with $0.340 for forging and machining. The difference in material costs for the two production methods was insignificant.

Each assembly was inspected visually and was required to show filler metal continuously around the joint. A gage check was also made to ensure that the two components were at right angles. Rejection rate was less than 2%.

Had it not entailed the purchase of a furnace, furnace brazing with copper alloy filler metal might have been used instead of induction brazing. (Furnace heating cannot be localized, but a copper brazed joint can withstand the 1500 F hardening temperature required for the ball race.) However, it was estimated that an annual output of 700,000 fittings (instead of 36,000) would be required to amortize the cost of a new furnace in three years.



Power supply	15-kw vacuum-tube unit
Frequency	450 kHz
Filler metal	0.047-in. wire, BAg-1
Flux	AWS type 3A
Heating time	12 sec
Production rate	77 trays per hour(a)
Rejection rate	Less than 1%(a)

(a) In torch brazing, the method previously used, production rate was only 29 trays per hour and rejection rate was 10%.

Fig. 10. Letter tray with two seams that were induction brazed, using the setup shown (Example 592)

Induction Brazing vs Alternative Joining Processes

Induction brazing is often a suitable alternative to other joining processes, depending largely on the size and shape of assembly and joint requirements.

In the four examples that follow, induction brazing replaced other joining processes for a variety of reasons. In the first and second of these examples, induction brazing replaced torch brazing and oxyacetylene welding, respectively. In the third example, induction brazing was used instead of shielded metal-arc welding of thin tubes. In the fourth example, distortion was reduced by changing to induction brazing from gas tungsten-arc welding.

Example 592. Use of Induction Instead of Torch Brazing (Fig. 10)

When torch brazing was used for joining the two seams on the open-end letter tray (the outside of which is shown in Fig. 10), the inside and outside of the brazed joints required careful cleaning and considerable grinding to obtain an acceptable finish. Also, one operator could braze only 29 trays per hour, and rejection rate was 10%.

To reduce the cost of excessive cleaning, grinding and rework, and to increase operator output, a change was made to induction brazing, with BAg-1 filler metal. This involved an investment of $12,000 for a vacuum-tube unit, $1700 for a heat exchanger, and $200 for two special inductors.

The inductors were formed from copper tubing. Water was circulated through the inductors and the power supply under pressure of 40 to 80 psi, and at a minimum rate of seven gallons per minute. To avoid condensation that might short circuit the inductor or power supply, cooling-water temperature was not allowed to fall below 70 F. This was done by circulating it through the heat exchanger. The coils of the inductor were specially shaped, as shown in Fig. 10, to concentrate heat at the joints. (For later production, inductors formed from round tubing were replaced with a pair made from 1/4-in.-square tubing and having mitered corners that fit the rectangular workpieces better and produced a more even heating pattern.) A fixture was constructed by bolting together two pieces of aluminum sheet that had been bent at right angles to support and locate the tray so as to give an air gap of 1/8 in.

The trays were formed from notched stock to a maximum clearance of 0.005 in. per joint, and the edges were wire brushed to remove burrs. The corners of the trays were then dipped in type 3A flux, and the trays were placed in the fixture, as shown in Fig. 10, and heated for 12 sec. When the

workpiece reached the flow temperature of the filler metal (approx 1150 F) and while the current was still flowing through the inductor, BAg-1 was face fed to a ¾-in. segment of each 2-in.-long joint; the remainder then filled by capillary action. Toxic fumes were removed by an exhaust.

After brazing, the trays were washed in a tank containing a 1-to-6 emulsion of soap and water, at 190 F, which removed 80 to 90% of the flux residue and also protected the trays from rusting. The brazed joints were then lightly sanded.

Two identical inductors were connected to one power supply. Thus the operator could load the fixture of one while the other was heating. In this way, 77 trays per hour were produced (compared with 29 by torch brazing). The rejection rate was less than 1% compared with 10% when torch brazing was used. Grinding and much of the cleanup and rework were eliminated. Cost of the induction brazing equipment was recovered in less than a year.

Quality was controlled by regular inspection of the appearance of the joints, and spot testing was carried out by pull tests on the corners.

Example 593. Change From Oxyacetylene Welding to Induction Brazing (Fig. 11)

Oxyacetylene welding was the method originally used to join low-carbon steel chair-back uprights, of 0.048-in.-wall, square, welded tubing 27¼ in. long, to low-carbon steel end caps ⅞ in. square by 0.060 in. thick. The welded joints had to be ground and polished, and many were rejected because of undercutting and porosity. Reject and rework rate was 10%. Hourly production per operator was 110 assemblies.

Induction brazing of five assemblies simultaneously in one inductor was selected to replace welding. Figure 11 shows the setup used. The power supply was a vacuum-tube unit, which operated on a 440-volt, three-phase, 60-Hz line. It had an output of 15 kw at a frequency of 450 kHz. The inductor, made of copper tubing, was arranged to accommodate five assemblies in a single turn and was shaped to heat at the joint surface and tilted to allow access to the fixture. Optimum air gap to the workpiece was about ⅛ in. The inductor and the power supply were cooled by water at a minimum rate of 7 gal per minute under pressure of 40 to 80 psi. A heat exchanger was used to keep the water temperature from falling below 70 F, to prevent condensation that might cause short circuits in the inductor and power supply.

The fixture consisted of a cemented-asbestos board on an aluminum support. It had ⅞-in. slots spaced about ½ in. apart to accommodate and locate five assemblies.

Five end caps were placed in the slots of the fixture and then a single strip of BAg-1 filler metal 0.005 in. thick by ¼ in. wide was laid over them in the position shown in Fig. 11. Each of the five uprights, which had been dipped first in trichlorethylene, to remove mill oil, and then in type 3A flux, was placed on the filler metal so that the filler metal was pressed between it and the end cap. The upper ends of the uprights were held by magnets.

When all five assemblies were in place, an induction heating cycle of 28 sec was started. Heating was greatest next to the upper (back) half turn of the inductor, so that when the filler metal melted (approx 1150 F), it flowed by capillary action toward the hottest part of the joint and filled the entire joint. While the filler metal was still molten, the end caps and the uprights were aligned manually with a short paddle made from cemented-asbestos board. (The inductor was lower in front of the work to allow access for the paddle.)

The brazed assemblies were washed in a tank containing a 1-to-6 emulsion of soap and water, at 190 F. This emulsion removed 80 to 90% of the flux residue and also acted as a rust inhibitor. The brazed joints were then lightly belt-sanded.

Quality was controlled by visual inspection. The rejection rate was less than 1%,

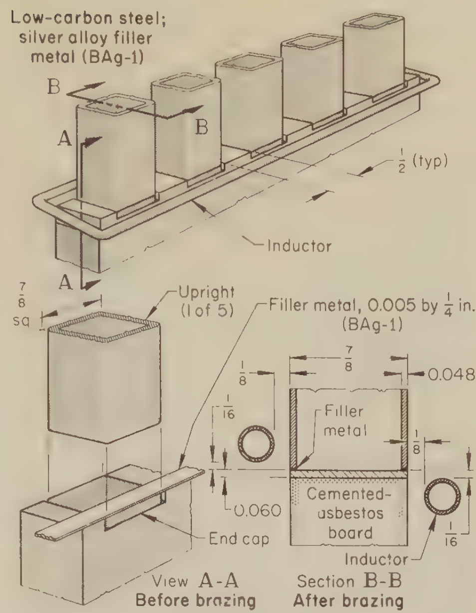


Fig. 11. Setup for induction brazing five chair-back uprights to five end caps at one time (Example 593)

as compared with 10% for oxyacetylene welding. Average production rate for one operator was 232 assemblies per hour — more than twice the rate for welding.

Example 594. Use of Induction Brazing Instead of Shielded Metal-Arc Welding (Fig. 12)

Originally, a 5⁄32-in.-wall resistance-welded and drawn low-carbon steel tube and a hot rolled 1045 steel collar were joined by shielded metal-arc welding. The joint design for welding is shown in Fig. 12. During welding, unintentional melt-through of the tube occurred occasionally. Moreover, the weld beads had to be ground for satisfactory appearance, and some of the welded joints cracked in service.

To improve the appearance of the joint and to increase strength, induction brazing was substituted for welding. Two joint designs were used for brazing, as shown in Fig. 12. In the first design, a single groove to take a preformed ring of filler-metal wire was machined in the collar, and the collar and tube were then threaded together. Before brazing, both parts were cleaned with trichlorethylene, and type 3A flux was brushed on the tube. Then a preformed ring of 1⁄16-in.-diam BAg-1 wire was inserted in the groove provided for it, and the parts were screwed together, mounted on centers and brazed using a 100-kw, 10-kHz power supply. The joint seemed strong, but in the field it failed by fatigue through the innermost thread.

In an improved joint design, the threads were eliminated and a second groove for filler metal was added. Filler metal for both grooves was 1⁄16-in.-diam BAg-1 wire, in preformed rings. Visual inspection after brazing showed a full perimeter of filler metal at both ends of the joint. The brazed assembly withstood an axial pull of 60,000 lb (equivalent to a shear stress of 30,000 psi), which was above service requirements. None of the assemblies that incorporated the improved joint design failed in service.

Brazing, employing the improved joint design, had the following advantages:

1. The assembly was stronger. The higher strength was attributed to the fact that, in the brazed joint, a large area of the joint between the collar and the tube was bonded, whereas in the welded joint, bonding was restricted to the collar ends.
2. Melt-through was eliminated.
3. The appearance of the joint was improved, and the grinding operation was eliminated.
4. Production rate was increased (see time comparison in the table with Fig. 12).

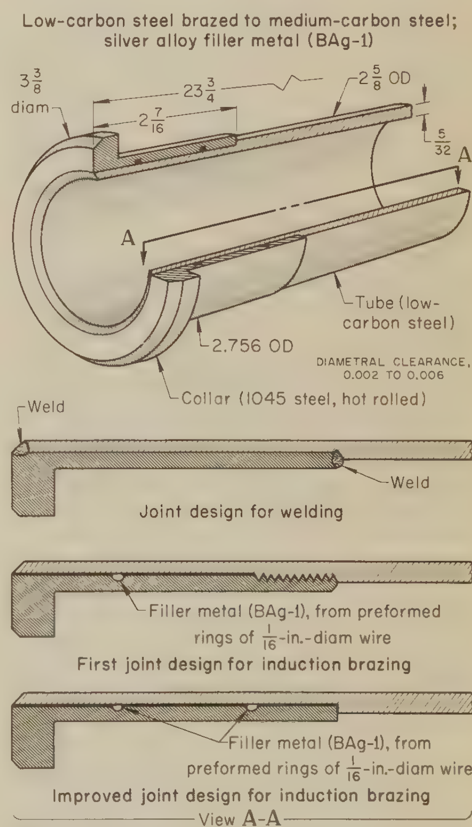
Example 595. Use of Induction Brazing Instead of Gas Tungsten-Arc Welding (Fig. 13)

An assembly of a component used in an air-operated pump was made by joining three parallel tubes, 13 5⁄16 in. long, to two machined end pieces (see Fig. 13).

Originally, the assembly was joined by gas tungsten-arc welding, but the difference in heat absorption by the tubes and the relatively massive end pieces caused excessive warping of the tubes. Because good alignment was necessary to prevent faulty operation of the pump, the tubes had to be straightened after welding. Cost for labor, including welding and straightening, was $0.847 per assembly.

Induction brazing, for which equipment was available, was selected to replace gas tungsten-arc welding. Brazing conditions are given in the table with Fig. 13. (The production quantity was too low for furnace brazing, and the cost of fixtures would have been too high.)

The inductor for the larger end piece (lower end piece in Fig. 13) was 2¼ in. long, had an inside diameter of 3¼ in. and was made of eight turns of ¼-in.-OD copper tubing. To prevent burning of the crests of the external threads on the end piece during the relatively long high-frequency heating, the heating of the threads was reduced by constructing the inductor in a manner to produce cancellation of the magnetic flux field in this area. This was done by winding the four turns on one end of the inductor in the direction opposite to that of the other four turns. The inductor for the smaller end piece (upper



Item	Welding	Brazing(a)
Time for Joining 30 Assemblies		
Setup time, hr	0.20	0.80
Joining time, hr	3.66(b)	2.37(c)
Total time, hr	3.86	3.17

(a) Using improved design shown. (b) 0.122 hr per assembly. (c) 0.079 hr per assembly.

Fig. 12. Tube-and-collar assembly in which brazing replaced welding, with appropriate changes in joint design (Example 594)

end piece in Fig. 13) was 2 in. long, had an inside diameter of 2⅝ in. and was made of four turns of ¼-in.-OD copper tubing. (The smaller end piece had no external threads and the inductor was wound without reverse turns.)

A special fixture, consisting of a base, an alignment bar, and two mounting plugs having threads that matched those of the end pieces, was used. This fixture had been designed to meet the following requirements: (*a*) allow room for the inductor, (*b*) hold the end pieces parallel and square with each other and square with the centerline within 0.004 in. TIR, and (*c*) hold the pitch diameters of the threads of the end pieces concentric within 0.010 in. TIR.

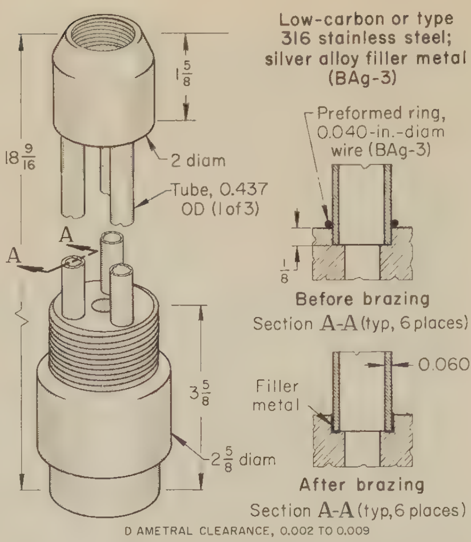
The tubes and end pieces were electrocleaned, pickled in hydrochloric acid, and electropolished. The tubes were dipped in type 3A flux, and preformed rings of 0.040-in.-diam BAg-3 filler-metal wire were slipped over them. (BAg-1 was not used, except in emergency, because it did not consistently make satisfactory fillets on stainless steel. Filler metal BAg-3 is generally preferred for brazing stainless steel and is satisfactory for brazing carbon steel.)

For rapid production, only one end was brazed in each production run. First, the large end piece was mounted on the fixture base, and the tubes and filler-metal rings were positioned. A mounting plug was screwed into the small end piece. Then the alignment bar was inserted through the plug (and end piece), the cluster of tubes and the large end piece, and was fastened in the fixture base. The inductor was turned on for approximately 138 sec, heating the joint to 1300 to 1375 F. The inductor was shut off by a timer, and the sub-brazement was removed from the fixture.

Then, in a separate operation, the small end piece was mounted on the fixture base, and the sub-brazement and filler-metal wire were positioned. A mounting plug was screwed over the large end piece. Then the alignment bar was inserted through the plug (and sub-brazement) and the small end piece, and was fastened in the fixture base. The brazing procedure was the same as for the other end; after brazing, flux was removed by rinsing and pickling.

The brazed assemblies were given 100% inspection, which included visual examination for proper joint fill and fillet, a gage check of alignment of faces and threads, and a hydrostatic pressure test at 800 psi when the assembly was installed in the pump. Rejection rate for the brazed assemblies was less than 1%. The brazed assemblies could be incorporated into the pumps without additional straightening.

Production rate was 13 assemblies per hour — or three assemblies per hour more than had been joined by gas tungsten-arc welding. Labor cost per piece for brazing was 70% of that for welding and straightening.



Power supply	25-kw vacuum-tube unit
Frequency	400 kHz
Brazing temperature	1300 to 1375 F
Heating time, each 3-joint end	2.3 min
Production rate	13 assemblies per hour
Labor cost per assembly	$0.592

Fig. 13. Pump-part assembly, induction brazed to minimize distortion (Example 595)

Two-Process Brazing. In the preceding example, two sets of joints in the same assembly were successively induction brazed in two stages. For some assemblies that incorporate two joints, it may be advantageous to use induction brazing for one joint and furnace brazing for the other joint. This sequence was employed in the next example.

Example 596. Use of Furnace and Induction Brazing for Different Joints in the Same Assembly (Fig. 14)

A housing-cover assembly for an automotive brake booster was fabricated by fastening a machined ferrule to one end of a welded tube and a press-formed cover to the other end, as shown in Fig. 14. The ferrule was made of cold rolled 1112 or 1113 steel; the tube and cover, of 1010.

The ferrule-to-tube joint (detail B in Fig. 14) lent itself to brazing in a controlled-atmosphere furnace, which was available in the plant. The cover-to-tube joint (detail A in Fig. 14) was subsequently brazed by induction, because the close final dimensions necessary could not be held in furnace brazing, and brazing in a furnace would distort the press-formed cover.

Before being furnace brazed, the ferrule and tube were spray cleaned with a hot alkaline solution and then assembled in an arbor press. The joint was designed for a press fit, with the 1.721-to-1.724-in. outside diameter of the ferrule joint surface and the 1.710-to-1.720-in. inside diameter of the tube producing interference of 0.001 to 0.014 in. A proprietary flux was brushed on the surfaces surrounding the joint, because the furnace atmosphere was not highly reducing, and a preformed ring of BCu-1 filler-metal wire was dropped into place inside the tube. The assemblies were then loaded, ferrule end down, onto graphite plates. The plates were subsequently loaded onto trays, 70 assemblies to a tray, and furnace brazed (for conditions, see table with Fig. 14).

For induction brazing, the subassembly was loaded over a locator-clamp in the induction brazing fixture (Fig. 14). In automatic sequence, this locator-clamp expanded and was drawn down to clamp the subassembly firmly in position.

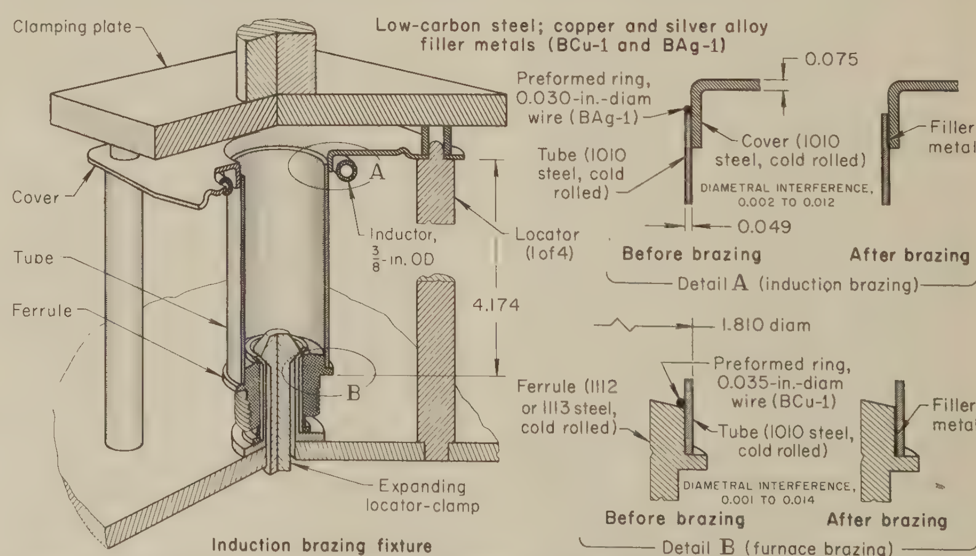
The cover was spray cleaned with a hot alkaline solution, type 3A flux was brushed inside the hole, and a preformed ring of BAg-1 filler-metal wire was set in place inside the hole. The cover was then put into the fixture and over the tube, and four locator posts on the fixture were inserted into four mounting holes in the cover (see Fig. 14). The joint was designed for a press fit to accommodate the tolerance of the tubing as-purchased, the 1.808-to-1.813-in. outside diameter of the tube and the 1.801-to-1.806-in. inside diameter of the cover at the joint producing a room-temperature interference of 0.002 to 0.012 in. (Differential expansion of tube and cover during heating allowed the filler metal to flow through the joint.)

Pressing two palm buttons started the following automatic sequence. The piston of a bottom air cylinder drew down the locator-clamp, expanding it and clamping the ferrule. The piston of a top air cylinder pushed the clamping plate down, which pressed the cover down onto the tube and the four locator posts, thus holding the 4.174-in. dimension between the cover and the flange on the ferrule. Heating time was 6 sec, followed by a 5-sec cooling air blast. The piston of the bottom cylinder pushed up the locator-clamp, releasing the ferrule, and then the piston of the top cylinder and the clamping plate retracted, releasing the cover. The assembly was unloaded by hand and cleaned of flux.

The single-turn inductor was positioned ⅛ in. below the cover; the gap between cover lip and inductor was 0.090 in.

Other Examples of Induction Brazing in This Volume

For information on induction brazing of other metals, see Examples 628 and 629 (stainless steel) and Examples 649 to 654 (copper alloys).



Furnace Brazing (Ferrule to Tube)	
Furnace type	Electric roller hearth(a)
Atmosphere	Exothermic, 2400 cfh
Brazing temperature	2050 F
Time in heat zone	39 min
Total time in furnace	2 hr

Induction Brazing (Cover to Tube)	
Power supply	20-kw vacuum-tube unit
Frequency	450 kHz
Heating time	6 sec
Air-blast (cooling) time	5 sec
Total cycle time(b)	20 sec

(a) Preheat zone, 15 ft; heating, 30 ft; fan cooling, 45 ft. (b) For clamping, heating, cooling.

Fig. 14. Housing-cover assembly in which one joint was furnace brazed and the second joint was induction brazed in the fixture shown (Example 596)

Resistance Brazing

RESISTANCE BRAZING is a resistance joining process in which the workpieces are heated locally and filler metal preplaced between them is melted by the heat obtained from resistance to the flow of electric current through the electrodes and the work. In the usual application of the process, the heating current is passed through the joint itself. Resistance welding equipment is used, and the pressure needed for establishing electrical contact across the joint is ordinarily applied through the electrodes. The electrode pressure also is the usual means for providing the tight fit needed for capillary behavior in the joint. The heat for resistance brazing can be generated mainly in the workpieces themselves, in the electrodes, or in both, depending on their electrical resistivity and dimensions.

Applicability. Parts of many different shapes can be resistance brazed, provided that the surfaces to be joined either are flat or conform over a sufficient contact area, and that they can be held together under pressure to permit the heating current to flow through the joint, and the filler metal to be distributed throughout the joint by capillary action. Workpieces that can be joined by resistance brazing range from wire 0.001 to 0.005 in. in diameter to assemblies having joint areas of about 10 to 15 sq in. Joint area in most high-production resistance brazing is small, usually not more than 0.1 to 0.6 sq in.

The use of portable welding heads or tongs permits resistance brazing to massive parts or structures and in locations inaccessible to standard resistance welding machines.

The process is used where the workpieces must be heated locally and maximum local temperatures must be below the melting point of the workpieces. In some applications, total heat input can be sufficiently small and localized to make joints for which conventional arc or resistance welding or other brazing methods are not suitable (see Preventing Overheating, page 653, and Examples 598, 602, 603 and 604). Filler metals that flow at 1100 to 1500 F are used in resistance brazing of most common metals.

Resistance brazing can produce joints that have bond areas many times as large as those of resistance spot or seam welds, and that have correspondingly greater strength. When resistance brazing is done in resistance welding machines, joining can be done at high production rates, at low labor cost, and with low operator skill.

Metals Joined. The work metal most frequently joined by resistance brazing is copper. Resistance brazing with high-resistivity electrodes or electrode facings is an efficient method of providing localized heating at the joint in this highly conductive metal, while avoiding fusion of the copper base metal. In addition, copper is the only commonly used metal that can be brazed in air with self-fluxing filler metals (copper-phosphorus alloys, BCuP type), and thus without the use of a flux.

The workpieces were made of copper in 12 of the 16 examples of resistance brazing in this volume, and in two other examples, one of the two workpieces was copper; BCuP-5 was used as a filler metal in 11 of the 14 examples in which copper was a work metal.

The metals that rank next in frequency of joining by resistance brazing are copper alloys. Copper alloy 184 (chromium copper) was one of the work metals in Example 606, and the difficult-to-weld copper alloys 360 (free-cutting brass) and 353 (high-leaded brass, 62%) were joined in Example 602. Copper alloys (and copper) have been resistance brazed in producing a variety of assemblies used in circuit breakers, electrical switchgear, and power-distribution equipment.

Electrical contacts made of silver, silver-graphite and silver-molybdenum have been resistance brazed to copper in making heavy-duty circuit breakers and other types of electrical equipment, in an important application of the process.

Steel was the work metal in Example 601 in this article, and was one of the two work metals in Example 660 in the article on Brazing of Copper Alloys. In plants where copper and copper alloy assemblies are resistance brazed, the process occasionally is applied also to assemblies made of steel or other metals. Typical resistance brazed low-carbon steel assemblies made in one such plant in quantities of 300 to 400 per year were transformer brackets made by joining hat-shape strips ⅛ in. thick by 1 in. wide to flat strips ⅛ by 1 by 6 in., making a 1-in.-square joint at each end of the flat strip with the aid of preplaced foil of BAg-1a filler metal.

Fins made of steel or other metals have been resistance brazed to low-carbon steel tubing for heat exchangers.

Stainless steel, nickel alloys, and aluminum are resistance brazed to a limited extent, and occasional use of the process has been made on other metals. Stainless steel internal baffle plates have been resistance brazed to the inner walls of 1020 steel tubes in heat-exchanger applications.

Equipment

Resistance brazing ordinarily is done with conventional resistance welding equipment as described in the article on Resistance Spot Welding. This equipment can be used for some resistance brazing applications without modification. Generally, however, heating and cooling times are longer and electrode force is lower for resistance brazing than for resistance spot welding. Resistance spot welding machines may be modified to provide ranges of operating conditions suitable for resistance brazing, or machines may be designed especially for resistance brazing. Other changes often needed to adapt resistance spot welding equipment for resistance brazing are in electrode holders and electrodes. Electrode holders that provide low inertia and fast follow-up are sometimes needed (see Use of Fast Follow-Up, page 651, and Examples 602 and 603).

Adaptation for high-volume production is generally the same as in resistance spot or projection welding, except for the additional need in most resistance brazing applications of providing for the preplacement of filler metal and, sometimes, flux in the joint.

Power sources for most resistance brazing are conventional resistance welding transformers, which deliver low-voltage, high-amperage power (see page 405 in the article on Resistance Spot Welding). A higher voltage is usually needed in the secondary circuit in resistance brazing than in resistance welding, especially when using high-resistance electrodes, and hence the transformer should have a relatively high kilovolt-ampere rating.

Capacitors or capacitor banks can be used as power sources for resistance brazing of wires or other small parts in joints for which the heat input must be extremely small and the heating time very short. Before each operation, the capacitors are charged with direct current from either a rectifier or a motor-generator (see page 475).

A capacitor was used as the power source for resistance brazing individual copper connector wires 0.002 to 0.005 in. in diameter to copper terminals clad with BCuP-5 brazing alloy in Example 603, discharging 2 to 3 watt-seconds of energy in a heating time of 2 to 3 milliseconds. A capacitor also was used for resistance brazing braided copper connector wires (each consisting of eight strands of 0.005-in.-diam wire) to high-carbon steel terminals electroplated with silver over copper, in Example 660 in the article on Brazing of Copper Alloys.

Controls for resistance brazing are the same as for resistance spot and projection welding (see page 402 in the article on Resistance Spot Welding). Brazing current, electrode force and timing usually are controlled automatically. Slope control and pulsing, where needed, can be programed into the machine. Electrode advance and retraction, and sequencing of some or all machine functions, can be done manually or automatically.

Fixed timing is sometimes unsatisfactory because it does not provide

This article has been prepared from contributions of members of the Committee on Welding and Brazing of Copper and Copper Alloys and the Committee on Brazing of Steel. Several of the examples were contributed by members of other Metals Handbook committees on welding and brazing.

compensation for variations in heat input to the joint from the electrodes or in the heat-sink capacity of workpieces, fixtures and other equipment during continuous production runs. Automatic termination of heating by a controller that senses temperature at or near the joint can provide uniform heating of the joint and filler metal, regardless of variation in heat input or heat loss, as in the next example.

Example 597. Use of an Infrared Sensor for Control of Heating for Automatic Resistance Brazing (Fig. 1)

The assembly shown in Fig. 1, a connector for an electric controller, was composed of a U-shape copper-strip contact finger brazed to a lug consisting of a short length of copper tubing that was flattened at the joint. No cleaning was necessary before brazing, because both members of the assembly had been tin plated.

Erratic joint strength was observed in the first production runs, in which the assemblies were joined by induction brazing. When the joining process was changed to resistance brazing to improve consistency of joint strength, it was necessary to adjust the heating time during continuous production runs to compensate for progressive heat buildup in the electrodes. Timing was accurate to within one cycle ($\frac{1}{60}$ sec).

The need for periodic adjustment of the heating time to obtain consistent joint strength was eliminated by changing from a time-control method of regulating heating to a method in which heating was automatically terminated by a controller actuated by an infrared photocell that sensed the work temperature near the joint. The sensor was sighted on the contact finger at the point shown in Fig. 1.

The filler-metal preform (see section A-A in Fig. 1) was a 0.63-in. square of 0.005-in.-thick BCuP-5. This filler metal, self-fluxing on copper, was selected to avoid the need for using a separate flux. In spite of the relatively low electrical conductivity (10% IACS) of BCuP-5, electrical resistance across the joint area (about 0.4 sq in.) was low enough in relation to the small current load (100 amp, max) carried by the connector in service. The machine used for brazing was a 75-kva, air-operated, press-type resistance welding machine. The electrodes had RWMA class 2 (chromium copper) shanks and class 14 (molybdenum) faces. The force applied to the electrodes was 350 lb. The brazing current was 18,000 amp and the brazing time averaged 50 cycles, or slightly less than 1 sec. Alignment of the workpieces was maintained by asbestos fixtures (not shown in Fig. 1).

The operator loaded the contact finger into the fixture, placed the filler-metal preform in position, placed the lug on top of the filler metal, and pushed the start button to close the electrodes and actuate the brazing sequence, which was completed without further attention by the operator.

Quality was controlled by random checks on the operation and the brazed assemblies. In addition to visual examination of the completed joints for presence of a fillet, randomly selected brazed assemblies were tested to destruction in a pull test. The brazed joint was required to remain intact in the destructive test. Equipment details and brazing conditions are given in the table that accompanies Fig. 1.

Machine Construction. The machines used for resistance brazing, which generally are conventional resistance welding machines, are ordinarily of press-type construction (see page 406 in the article on Resistance Spot Welding), in which the upper electrode and welding head move in a straight line and thus assist in maintaining alignment of the workpieces during brazing.

Machines for intermediate to high production are usually floor-standing or bench-mounted air-operated types, as in 12 of the 16 examples of resistance brazing in this article and in the article on Brazing of Copper Alloys.

Portable machines, although ordinarily rated for lighter duty than floor-standing or bench-mounted machines, may have the same capabilities in all other respects (see page 406 in the article on Resistance Spot Welding). The portable head can be of a size suitable for use in close quarters and for carriage mounting in applications where the brazing head must travel. In the example that follows, resistance brazing with a carriage-mounted welding head was combined with other assembly operations in a manufacturing line.

Example 598. Incorporation of Cross-Wire Resistance Brazing Into a Mechanized Coil-Winding Operation (Fig. 2)

The 36-to-48-in.-long coil shown under construction in Fig. 2 was used to read out positions of machine-tool components on a numerically controlled machine tool. For this purpose, precisely located tap leads were brazed to the coil wire at predetermined intervals in a straight line along the coil. As many as 48 taps were made on a single coil, and in order to ensure the precision of the readout, the taps had to be located within ± 0.003 in. of true position.

Flexible wires for the tap leads were resistance brazed to the coil wire in cross-wire joints while the coil was being wound. For this purpose, a portable resistance welding head was mounted to the winding machine in such a way that it could move along the 36-to-48-in.-long coil into position for attaching each tap lead. The electrodes were $\frac{1}{4}$-in.-diam molybdenum rods that were grooved — the lower one to take the coil wire, and the upper one at right angles to the lower groove to accommodate the tap lead. (See detail A in Fig. 2.)

Both wires were of tinned copper corresponding to ASTM B3 — soft or annealed copper wire for electrical purposes, which ordinarily is alloy 110 (ETP copper) or low-resistance lake copper. The thickness of the tin coating was about 30 to 50 micro-in.

The coil wire was a single strand 0.032 in. in diameter; the tap-lead wire consisted of ten strands of copper, each 0.010 in. in diameter, and was covered with a plastic insulating coating. The insulation was manually stripped from the joint area at the end of the stranded tap-lead wire before brazing.

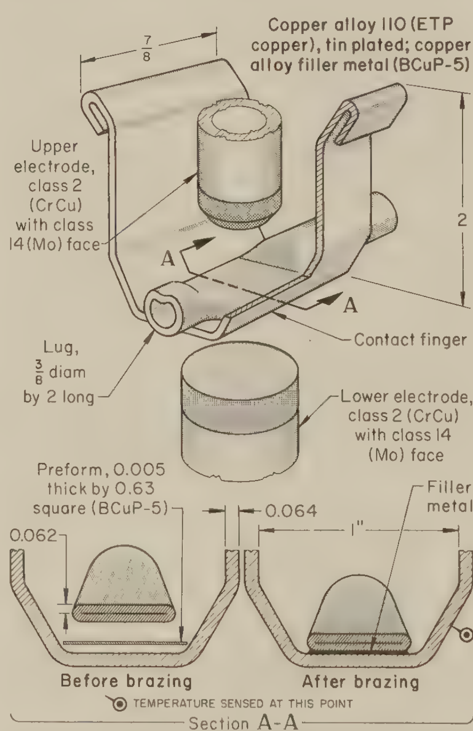
The BCuP-5 filler metal was furnished in strip 0.030 in. wide by 0.005 in. thick. Because the workpieces were tinned, the joint surfaces did not need cleaning, and because of the phosphorus in the filler metal, they did not need fluxing. The wires and the filler metal were furnished on spools, from which they were fed during production of the coils.

In operation, the operator pushed a button, and the coil-winding machine automatically wound the correct number of turns of coil wire onto the threaded insulating core. The coil wire from the spool was guided between the electrodes by a grooved phenolic plate. The operator drew the filler-metal strip, which was guided by a groove in the filler-metal guide, across the coil wire, stripped the insulation from the end of the tap-lead wire and laid the bare end over the filler-metal strip so that the tap-lead wire lay in its guide groove. A gage at the end of the guide for the tap-lead wire indicated the proper cutoff length (see detail A in Fig. 2).

At the press of a button, the electrodes closed and the joint was brazed. Timing of the brazing sequence was controlled by a solid-state timing device. Each joint was made at a point on the coil wire exactly one turn away from its final position. The filler metal and the tap-lead wires were trimmed by hand, and the final turn was made manually to bring the tap lead into final position on the coil. The operator inspected the joint, trimmed the excess tap-lead wire at the joint at the proper angle (75° from horizontal), placed a polyester insulating strip between the tap lead and the adjacent turn of the coil to avoid shorting that would give false readouts, and bent the tap lead to fit closely against the body of the coil. (Detail B in Fig. 2 shows completed assemblies of tap leads to a coil wire; detail C in Fig. 2 shows the setup for brazing and the assembly after brazing and trimming and after insulating and bending.) The operator then placed the end portion of the tap lead in a spring-type retaining fixture mounted on a circular disk (shown at right in the top view in Fig. 2) that was temporarily attached to the end of the coil core for holding the brazed tap leads during the remainder of the operation.

Joints had to be 100% sound in order to be electrically efficient. Five sample joints were made by the operator before the start of each coil, at the beginning of each shift, and after any interruption of about 1 hr in production, for machine qualification. The sample joints were checked visually for the presence of fillets, and joint strength was measured on each in a pull test. The mean breaking load for the five specimens had to be 24.3 lb min, and the range could not exceed 5.75 lb.

Production was not started (or resumed after an interruption) until acceptable test results were obtained. Making and evaluating the sample joints took about 5 min. During production, brazed joints were spot



Machine	Press-type, air-operated, 75-kva automatic resistance welding machine
Loading and unloading	Manual
Filler metal	BCuP-5, 0.005-in.-thick preforms
Flux	None
Electrodes	RWMA class 2 (chromium copper) with class 14 (molybdenum) facings
Electrode force	350 lb
Brazing current	18,000 amp
Heating time	Approx 50 cycles (controlled by infrared sensor; see text)
Hold time	40 cycles
Fixtures	Asbestos, for alignment of workpieces

Fig. 1 Electrical-connector assembly that was automatic resistance brazed using an infrared sensor to control heating time (Example 597)

checked visually for the presence of fillets. Rejects for quality of brazed joints averaged about 1%. Rejects for faulty positioning were negligible.

Resistance brazing was preferred to a mechanical attachment technique, which had been tried on prototype coils, because of the greater reliability of brazed connections and because of production problems anticipated for the mechanical technique. Attaching the tap leads by welding would have required higher temperatures, with the likelihood of burning the small strands of the tap-lead wire; soldering would have produced weaker joints with a lower operating-temperature limit in service. Equipment details and brazing conditions are given in the table that accompanies Fig. 2.

Hand-Held Tongs. A simpler type of portable resistance brazing machine is equipped with hand-held tongs that can be used conveniently to make brazed connections on massive assemblies that cannot be brought to a conventional resistance welding machine.

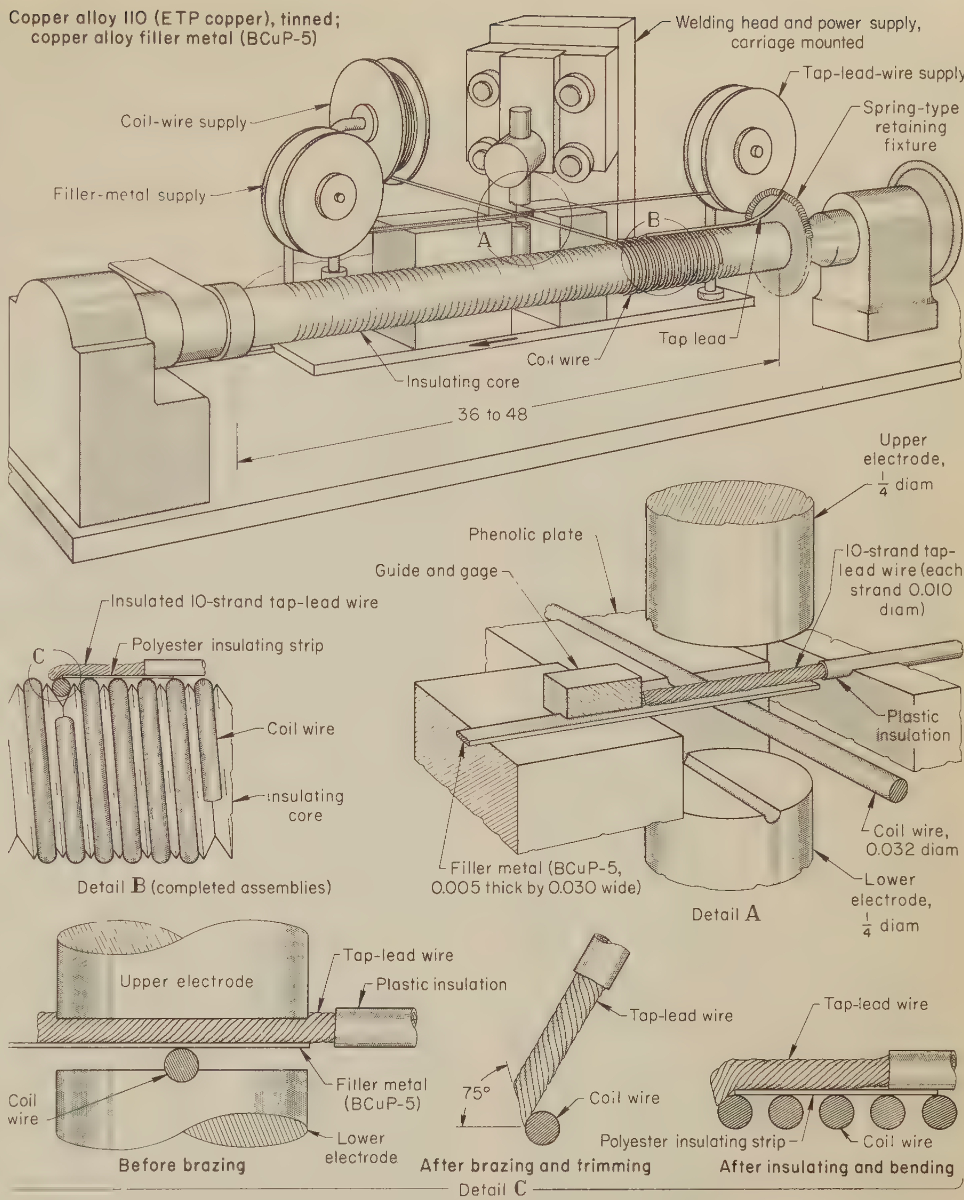
In the most rudimentary form, the hand-held current-carrying tongs, with electrodes attached at the end of each arm, are squeezed together by the operator to exert pressure on the electrodes and the work, and the current is turned on and off and adjusted manually by the operator. The amount of current passed through the joint, the duration of heating and the repetition rate may make it necessary to water cool the flexible current-carrying cables that connect the tongs to the power source (usually a conventional resistance welding transformer), and the tongs may also be water cooled.

Except for the very lightest units, the tongs or portable welding gun is suspended from an adjustable counterbalancing unit for convenient manipulation by the operator. The electrode force on most units is applied by air pressure, and a hydraulic booster is sometimes used. The tongs or welding gun can be constructed so that the electrode force is applied in a straight line, to avoid disturbing the alignment of the workpieces during the brazing operation.

In Example 658 in the article on Brazing of Copper Alloys, water-cooled hand-held tongs and water-cooled cables were used in resistance brazing copper connections to terminals in electrical equipment. In Example 659 in the same article, water-cooled tongs and cables were used in resistance brazing 0.098-by-8-in.-wide strip to ¼-by-4-in. bus bar. However, water-cooling equipment was not used in resistance brazing 0.010-by-1¾-in.-wide strip to 0.012-by-½-in. bus bar in the same example; in this application, overlapping multiple spot brazes were made, with electrode contact areas of 1 sq in. and 0.11 sq in., respectively. In Example 604 in the present article, water-cooled tongs and cables were used in resistance spot brazing patches on the inner conductor tube of ocean cable.

Metal Electrodes

Selection of electrode material for resistance brazing depends on the electrical conductivity of the work metal or work metals to be joined, the design and dimensions of the joint, appearance requirements for the brazed product, susceptibility of the work metal to



Machine	Portable resistance welding machine, with bench-type head mounted on traveling carriage, incorporated into coil-winding machine (see text)	Electrode force	20 lb
Loading and unloading	Manual	Method of applying force	Air
Filler metal	BCuP-5	Brazing current	2450 amp
Flux	None	Heating time	60 cycles
Precleaning	None(a)	Hold time	30 cycles
Electrodes	RWMA class 14 (Mo), ¼-in. diam(b)	Timing method	Solid-state timer
		Joint strength(c):	
		Mean	24.3 lb, min
		Range	5.75 lb or less

(a) Insulation manually stripped from tap leads. (b) With 0.010-in.-deep (0.022-in.-radius) locating grooves on faces (c) Determined by performing a pull test on five sample joints.

Fig. 2. Arrangement for cross-wire resistance brazing of stranded copper-wire tap leads to solid copper wire while the solid wire was being wound into a coil (Example 598)

damage or marking, pressure needed on the work, production quantity of brazed joints, and cost of reconditioning or replacing an electrode.

Usual Materials. Electrodes for resistance brazing usually are made either of the standard electrode materials used in resistance spot welding, or of carbon. Low-resistivity metallic electrodes can be used for resistance brazing metals that have high to moderate resistivity; electrodes or facings made of highly resistive materials must be used for brazing low-resistivity metals. In the former instance, most of the heat for brazing is generated within the workpieces; in the latter, most of the heat is generated within the electrodes and is conducted to the work.

The materials used most frequently in resistance brazing are RWMA class 2 (chromium copper), RWMA class 14 (molybdenum), and various grades of carbon-graphite and graphite. Other standard and special electrode materials are sometimes used for special applications. Properties of the standard metallic electrode materials are given in Tables 2 and 3 in the article on Resistance Spot Welding (see page 409).

Class 2 (Chromium Copper). Electrode holders and shanks of faced electrodes for resistance brazing are usually made of RWMA class 2 material (chro-

Table 1. Properties of Five Carbon Electrode Materials Used in Resistance Brazing

Electrode material	Electrical resistivity, ohm-in.	Scleroscope hardness	Flexural strength, psi (min)	Apparent density, g per cu cm
Carbon-graphite, hard(a)	0.00080	70	3500	1.74
Carbon-graphite, hard, oxidation resistant(b)	0.00080	70	3500	1.75
Carbon-graphite, soft	0.00075	40	2400	1.57
Electrographite(a)	0.00042	50	2500	1.73
Electrographite, oxidation resistant(b)	0.00042	50	2500	1.75

(a) This type of carbon electrode material is also commonly used in air carbon-arc cutting, as described on page 301 in Volume 4 of this Handbook. (b) Similar to the electrode material listed immediately above, but impregnated with a small percentage of an oxidation retardant, usually an inorganic compound containing boron or phosphorus, for longer life.

mium copper), which is a general-purpose resistance welding electrode material with a minimum electrical conductivity of about 75% IACS.

Class 2 electrodes usually are used for resistance brazing of work metals that have high to moderate electrical resistivity, because sufficient heat for brazing can be generated in the work metal itself. In Example 602, class 2 electrodes were used to permit localized heating in the joint and the use of a small total heat input in joining copper alloys 360 (free-cutting brass) and 353 (high-leaded brass, 62%), each of which has an electrical conductivity of 26% IACS. For resistance brazing low-carbon steel parts in Example 601, a class 2 upper electrode with a class 14 (molybdenum) facing was used to augment the heat generated in the workpieces. To avoid excessive heating in the lower workpiece, to which a fiber gear was attached, the lower electrode was class 2 without a facing.

Refractory Metal Electrodes. Class 14 (molybdenum) is intermediate in mechanical and electrical properties among the refractory metal electrode materials, and has a nominal electrical conductivity of 30% IACS. This material and class 13 (tungsten), because of their resistance to high temperatures and their nonsticking characteristics, are the only common electrode materials that have long life in resistance brazing of copper and other highly conductive nonferrous metals. They are about equal in electrical conductivity.

Class 14 (molybdenum) is generally preferred because class 13 (tungsten) is harder to machine and is likely to develop radial cracks in service. For reasons of economy, it is common practice, where applicable, to use facings, buttons or inserts of the refractory metal instead of making the entire electrode of the refractory metal.

Class 14 (molybdenum) electrodes were used in resistance brazing copper parts in Example 598 in this article and in Examples 655, 656 and 657 in the article on Brazing of Copper Alloys. Class 14 facings were used on class 2 (chromium copper) electrode shanks in resistance brazing copper parts in Examples 597 and 605 in this article, and in Example 658 in the article on Brazing of Copper Alloys.

Class 13 (tungsten) electrodes were used in high-speed resistance brazing of braided copper wire to high-carbon steel that had been plated with silver over an undercoat of copper in Example 660 in the article on Brazing of Copper Alloys. In this application, an electrode material with fairly low conductivity, reasonably good mechanical properties, and resistance to wetting by and alloying with silver or copper was needed; class 13 (tungsten) electrodes had a low wear rate when used to exert a force of 8 lb on the braided wire.

Special electrode materials are sometimes needed to meet the unusual requirements of specific resistance brazing applications. In Example 603 in the present article, an electrode made of 60Pt-40Rh was used to provide long life in high-speed mass-production resistance brazing of insulated copper wires to copper terminal pads clad with BCuP-5. In this application, the electrode had to withstand (*a*) the heating that was used for melting the polyurethane insulation on the copper wire, (*b*) contact with molten BCuP-5 filler metal, and (*c*) heating in air that was used for burning off insulation residues after each brazed connection was made. The electrode reached a temperature of 1700 F. (This electrode was manufactured by percussion welding, as described in Example 177.)

Carbon Electrodes

Carbon electrodes used in resistance brazing ordinarily are of two general types — carbon-graphite and electrographite (artificial graphite). These electrode materials are made by simultaneously heating and blending the finely divided raw materials with coal tar pitch, which serves as a binder.

The stock from which resistance brazing electrodes are made comprises a few of the many grades of carbon stock that are manufactured primarily for use in casting ferrous and nonferrous metals. When they are used as resistance brazing electrodes, their very high electrical resistivity, which is much higher than that of the commonly used metallic resistance brazing electrode materials (classes 2 and 14), permits the generation of a larger quantity of resistive heat than do the metallic electrode materials. Accordingly, carbon electrodes are used chiefly in resistance brazing of copper and other highly conductive (low-resistivity) work metals. They are less expensive than metallic electrodes in raw-material cost and fabrication cost, but wear more rapidly, oxidize in air at operating temperatures (red heat), and cannot withstand pressures as high as those used on metallic electrodes. Thus the use of carbon electrodes in resistance brazing is restricted to brazing of small quantities of parts for which low electrode pressure is satisfactory.

Composition and properties of the commercial carbon electrode materials vary, and there are no generally accepted industry standards and terminology. The properties of five grades that are generally typical of the materials used in carbon electrodes for resistance brazing are given in Table 1.

Carbon-Graphite. The first three types of electrode materials listed in Table 1 are called carbon-graphite, and are made from mixtures of finely ground petroleum coke (carbon) and natural or artificial (electro) graphite with coal tar pitch. They are extruded in suitable shapes and heated in an electric furnace at about 1500 F to give them the desired properties shown in Table 1. The heating converts about half of the pitch to carbon, and the remainder is driven off as gases.

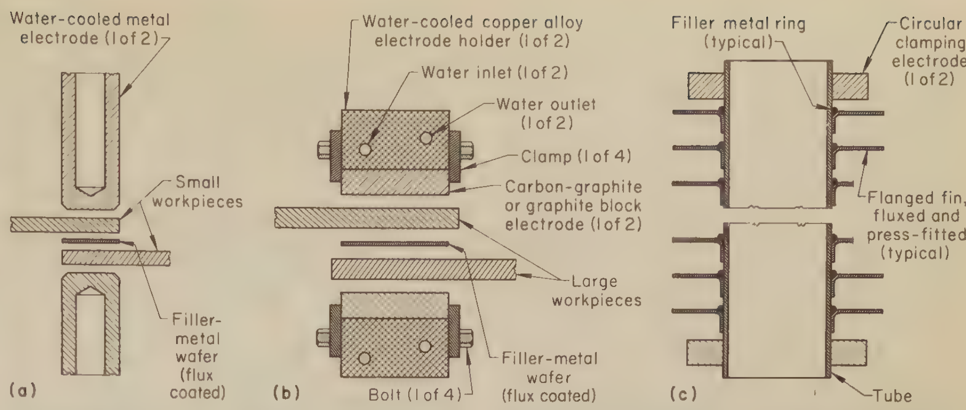
The final properties can be varied from those shown by changing the proportions of the raw materials, the particle size, and the time and temperature of heating. Increasing the ratio of graphite to carbon in the mixture, prolonging the heating time or increasing the temperature will lower resistivity, hardness and strength. Density is influenced chiefly by particle size.

Oxidation resistance of some grades of carbon-graphite is improved, for longer electrode life, by impregnating the cured material with a small percentage of an oxidation retardant, which is usually an inorganic compound that contains boron or phosphorus. In Table 1, oxidation-resistant grades 2 and 5 are the same as grades 1 and 4, respectively, except for the presence of an additive of this type.

Electrographite electrode material is made in the same way as the carbon-graphite grades, except that the extruded mixture of raw materials is heated at about 4500 to 4900 F, thus converting it to graphite (called artificial graphite or electrographite). Properties of a representative material of this type are given in Table 1, along with those of an oxidation-resistant or long-life impregnated form of the same material. Resistivity, hardness and flexural strength of electrographite electrode materials are substantially lower than for the hard carbon-graphite electrode materials.

Selection of Carbon Electrode Material. The general types of carbon electrode material shown in Table 1 (carbon-graphite and electrographite) have almost completely replaced the formerly used "straight carbon" types, which are made by heating finely ground petroleum coke and a binder at about 1500 F. The straight carbon grades typically have an electrical resistivity of about 0.0020 ohm-in. and a scleroscope hardness of about 100, and machining of these materials is much more difficult and costly than is machining of carbon-graphite and electrographite.

The hard carbon-graphite types are general-purpose materials and are preferred for most resistance brazing done with carbon electrodes, as brazing temperatures can be reached with less current than when the less resistive electrographite types are used. Electrographite is preferred for resistance brazing of metals that have a high surface resistance, particularly when one of the metals being joined is steel or another iron-base alloy. Soft carbon-graphite material combines high heating capacity with a low tendency to



Arrangements for resistance brazing of (a) *small flat parts using opposed water-cooled metal electrodes (conventional resistance welding type),* (b) *large flat parts using opposed carbon block electrodes attached to water-cooled copper alloy electrode holders, and* (c) *flanged fins to a tube using circular clamping electrodes*

produce local hot spots on the work metal, but has comparatively low wear resistance.

In resistance brazing with carbon electrodes, nonuniform current flow and resultant local overheating of the electrodes can shorten electrode life excessively. To prevent this, carbon electrodes must be tightly fitted into matching tapered adapters or clamped securely to the electrode holder, making contact with the holder over as large an area as possible, and provision must be made for adequate flow of cooling water in the electrode holder. Also, some carbon brazing electrodes are electroplated or sprayed with a copper coating about 0.002 in. in thickness, to reduce contact resistance against the electrode holder and to minimize internal temperature buildup in the carbon electrode.

The first and fourth grades in Table 1 are the same types of material commonly used in air carbon-arc cutting, as described on page 301 in Volume 4 of this Handbook.

Carbon electrodes were used in resistance brazing copper parts in Examples 599, 600 and 606 in this article, and in Example 659 in the article on Brazing of Copper Alloys. Hard carbon-graphite blocks were used in Example 599; electrographite blocks, in Example 600; and medium-hard carbon-graphite electrodes (having a resistivity of 0.0005 ohm-in.) in Example 606.

In resistance brazing with hand-held tongs in Example 659, 1-in.-square carbon-graphite electrodes were used with water-cooled tongs, while ⅜-in.-diam electrodes of the same material (which were used without water cooling) were coated with copper for longer life and to improve contact between electrode and electrode holder.

All four of the examples of resistance brazing with carbon electrodes were low-production applications where relatively rapid wear of electrodes, as compared with normal wear of metallic electrodes, could be tolerated.

Design of Electrodes

Commercially available resistance spot welding electrodes are used where the design and dimensions of workpiece and joint permit. The electrode tip is machined where necessary to provide a tip shape and face dimensions suitable for the work.

Carbon electrodes, depending on the size and design of the work, are in the shape of either standard metallic electrodes or flat blocks that may be several inches in length and width (size is usually limited by ability to obtain uniform heating and water cooling, or by the current capacity of the power source). When a high-resistance or long-wearing electrode material is required, it is often used in the form of facings, inserts or buttons that are attached to electrode shanks or bodies made of a less-expensive material.

Electrode design is developed to work with workpiece and joint design in eliminating the need for holding and locating fixtures or clamps wherever possible, and in permitting rapid and easy loading and unloading of workpieces, filler metal and flux.

Provision for water cooling of electrode holders and electrodes is generally the same as in resistance welding (see the article on Resistance Spot Welding, beginning on page 401).

Arrangement of Electrodes

In most resistance brazing, the electrodes apply the brazing force and are arranged in line with the workpieces between them.

This arrangement of electrodes, workpieces and filler metal is shown in the figure at the top of this page. Part (a) of the figure shows a typical arrangement for resistance brazing small flat parts (or small flat portions of larger components) between opposed water-cooled metal electrodes of the conventional resistance welding type.

Part (b) of the figure represents a generally similar arrangement for resistance brazing large flat parts, usually of a highly conductive metal such as copper, between opposed carbon block electrodes attached to water-cooled copper alloy electrode holders.

In making some butt joints, or where space limitations or work configurations do not permit the use of opposed electrodes, the electrodes are merely connected on either side of the joint to provide the brazing current, and other means are used to apply the brazing force to the joint.

Press-fitted internal or external members can be resistance brazed to tubes or other workpieces of cylindrical shape without the application of force. Electrodes are attached to the ends of the tube, and the brazing current is passed not through the joint, but only through the tube. A filler-metal ring is preplaced at the joint, and the internal or external members to be attached are fluxed before they are press fitted. This technique has been used to a limited extent in resistance brazing of internal stainless steel baffle plates and external steel or copper fins to 1020 steel tubes in heat exchangers, as shown in part (c) of the above figure.

Filler Metals

Of the large number of filler metals available, only a few are used extensively in resistance brazing. Selection of filler metal for resistance brazing is similar to that for other brazing processes, as discussed in detail in the articles on those processes, and in the articles on the brazing of cast irons, stainless steels, aluminum alloys and copper alloys.

More attention is given in resistance brazing than in other brazing processes to selecting from the metallurgically compatible filler metals the one having the lowest brazing temperature, because in resistance brazing it is necessary to keep the maximum local temperature reached by the work as low as possible, while providing uniform heating of the abutting joint surfaces and the filler metal. Fluidity of the filler metal is not critical in most resistance brazing, because the filler metal is usually preplaced and the bond area is relatively large.

The general types of filler metal usually selected for resistance brazing various classes of work metals are:

Work metal	Filler metal
Steel, stainless steel, heat-resisting alloys, copper, copper alloys, nickel alloys	Silver alloys (BAg type)
Aluminum alloys	Al-Si alloys
Copper and copper alloys	Cu-P alloys

These types of filler metal all have relatively low brazing temperatures.

Silver Alloys (BAg Type). Of this group of filler metals, the two most commonly used are BAg-1 and BAg-1a (see Table 1 on page 686 in the article on Brazing of Copper Alloys). BAg-1 and BAg-1a are free-flowing alloys that permit the use of low brazing temperatures. In addition, their narrow melting ranges (20 F and 15 F, respectively) prevent liquation, making them insensitive to variations in the rate of heating or cooling. Their narrow melting ranges are also advantageous in step brazing (see page 648).

For making corrosion-resistant brazed joints in stainless steel, BAg-3 and BAg-18 are preferred.

In the examples in this article, BAg-1 was used in resistance brazing steel parts in Example 601 and leaded brasses in Example 602, while BAg-1a was used in resistance brazing solidified ends of braided copper conductor cable to copper in Example 605 and to chromium copper in Example 606.

Aluminum-silicon alloys (BAlSi type) used in resistance brazing of aluminum alloys are listed in Table 1 on page 675 in the article on Brazing of Alu-

minum Alloys. These low-melting alloys are available in sheet or wire form; BAlSi-2 and BAlSi-5 are also available as cladding on aluminum brazing sheet. Temperature must be controlled with special care in brazing of the lower-melting brazeable aluminum alloys, such as wrought alloy 6151 and cast alloys 43 and 356, for which the melting range of the filler metals approach closely or overlap the melting range of the work metal.

Copper-phosphorus alloys (BCuP type) are widely used as filler metals for resistance brazing of copper and copper alloys. They are low-cost, general-purpose filler metals and have the special advantage of being self-fluxing on copper (although flux is ordinarily needed when using them on copper alloys, as phosphorus does not reduce metallic oxides other than those of copper). BCuP-5 is by far the most widely used of the group. In some applications on copper or copper alloys, the wider melting range, higher working temperature, and lower ductility of the BCuP filler metals make them less suitable than the BAg types.

BCuP-5 filler metal was used in ten examples of resistance brazing of copper in this article and in the article on Brazing of Copper. BCuP-2 and BCuP-5 were used in turn in making two resistance step brazed joints in sequence in Example 599.

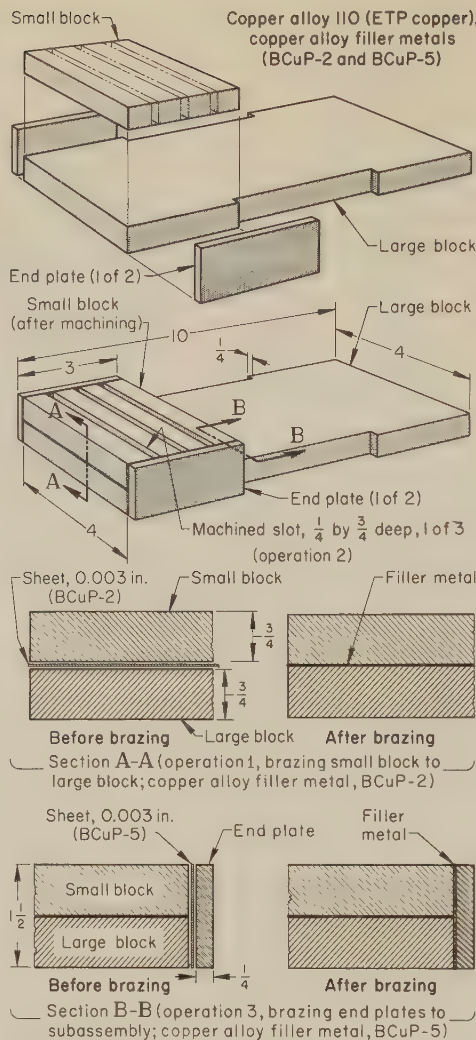
For higher ductility and corrosion resistance, silver brazing alloys sometimes are preferred to the BCuP filler metals for brazing of copper, in spite of the resulting need for fluxing, as in Examples 605 and 606. Difficulty in restricting flow of BCuP filler metals to joint surfaces may be a disadvantage.

Filler Metals for Step Brazing. When two or more joints are to be resistance brazed in sequence at points not widely separated on the same assembly, filler metals that differ in working temperature are selected, and the higher-melting filler metal is used first. Some overlap of the brazing temperature ranges can be tolerated, depending on the work metal, the size of the parts, proximity of the joints, the presence or absence of heat sinks, and the closeness of control of temperature.

Three general-purpose filler metals were used for all resistance brazing in one plant, in which the work metals were copper, copper alloys, carbon steel and electrical contact materials. The filler metals and their important characteristics were:

	Solidus temp, F	Liquidus temp, F	Brazing-temperature range, F
BCuP-2	1310	1460	1350 to 1550
BCuP-5	1190	1475	1300 to 1500
BAg-1a	1160	1175	1175 to 1400

Step brazing of copper and copper alloys was done on a variety of assemblies using these filler metals in sequence in any combination of two, as needed, brazing first with the filler-metal composition with the higher brazing-temperature range. In the example that follows, the two copper-phosphorus filler metals (BCuP-2 and BCuP-5) were used in resistance step brazing a simple but fairly massive assembly of four parts, for which the areas of the three joints were 12, 4½ and 4½ sq in.



Machine ....Press-type, air-operated, 50-kva resistance welding machine
Loading and unloading ....Manual
Timing ....Manual
Electrodes ...Hard carbon-graphite blocks, ¾ in. thick, clamped to RWMA class 2 (chromium copper) electrode holder
Precleaning ....Solvent degreasing
Production quantity .....30 assemblies (approx)

	Operation 1	Operation 3
Filler metal(a):		
AWS classification	BCuP-2	BCuP-5
Flow temperature	1350 F	1300 F
Working temperature .	1500 F	1325 F
Flux(b)	Type 3A	Type 3A
Electrode size, in.	3 by 4	2 by 3
Electrode force, lb	30	30
Brazing current, amp ...	40	40
Heating power, kva	40	25
Heating time, sec(c)	50	40
Hold time, sec(d)	15	15

(a) Foil 0.003 in. thick. (b) Water-diluted paste was brushed on contact area of workpieces just before brazing. (See page 628 in article on Torch Brazing for identification of flux type.) (c) Current was turned off when filler metal was seen to melt. (d) Electrodes were released and work was removed when filler metal was seen to solidify.

Operation 1. Braze small block to large block (section A-A above).
Operation 2. Mill three slots ¼ in. wide by ¾ in. deep across full width of subassembly.
Operation 3. Braze two end plates to subassembly simultaneously (section B-B above).

Fig. 3. Circuit-breaker subassembly that was made from four parts by machining and resistance step brazing, using filler metals of different brazing temperature ranges, with reduced machining time and less waste of work metal than with original method of making the assemblies from three parts by machining and torch brazing (Example 599)

Example 599. Use of Resistance Step Brazing, With Filler Metals of Different Brazing Temperature Ranges, To Reduce Machining Time and Waste of Work Metal (Fig. 3)

The lower terminal for a 1200-amp circuit breaker (see Fig. 3) was originally made by machining the main portion of the terminal from a 1½-in.-thick solid bar of copper and then attaching the end plates by torch brazing. Nearly half of the copper was removed by milling when this method of manufacture was used.

In an improved method, the terminal was made from the four pieces of copper shown in Fig. 3 by resistance brazing and machining in three operations, as follows:

1. Braze small (3-by-4-in.) block to large block (section A-A in Fig. 3).
2. Mill three slots ¼ in. wide by ¾ in. deep across the full width of the subassembly.
3. Braze two end plates to subassembly simultaneously (section B-B in Fig. 3), using a lower-temperature brazing filler metal than in Step 1.

Changing to the improved method reduced the amount of copper machined away to about ⅛ of the amount originally removed, and substantially lowered material and labor cost. It was less expensive to braze the 3-by-4-in. block to the larger block and then to mill slots than it was to locate and braze four small pieces to the large block to form the slots.

A press-type, air-operated resistance welding machine fitted with hard carbon-graphite block electrodes clamped to large rectangular water-cooled class 2 (chromium copper) electrode holders was used. For each brazing step, the contact areas of the workpieces were brush coated with a paste of type 3A flux that had been further diluted with water, sheets of 0.003-in.-thick filler-metal foil were put in place, and the assembled parts were placed between the carbon electrodes. The flux was used to prevent oxidation of the work surfaces during the heating, although BCuP-2 and BCuP-5 are usually considered self-fluxing in brazing copper.

Filler metal for Step 1 was BCuP-2, which flows freely at 1350 F (flow temperature) and which was used at a working temperature of 1500 F; filler metal for Step 3 was BCuP-5, which flows freely at 1300 F and which was used at 1325 F.

The operator turned off the heating current when filler-metal flow was observed, and released the electrode pressure and removed the work when the filler metal was seen to solidify. Additional equipment details and brazing conditions are given in the table with Fig. 3.

A total of about 30 lower-terminal assemblies were resistance brazed in this way as replacement units for circuit breakers that had failed in service.

Form and Application of Filler Metal. Filler metal for resistance brazing is usually preplaced in the joint in the form of foil, wire, ribbon or a washer about 0.003 to 0.005 in. thick and of a shape and size to cover the approximate contact area of the joint. Filler metals not available in these forms can be preplaced in the joint in the desired amount as a powder, paste or preform that may also contain flux. High-speed injection can be used in mechanized operations, taking precautions to prevent separation and settling and to ensure the addition of a sufficient quantity of the filler-metal paste.

One technique for preplacing powdered filler metal is to dip the prefluxed parts into the powder, using flux of a viscosity selected to pick up the desired thickness of filler-metal powder. In some resistance brazing applications, one or both workpieces may be plated, clad or coated with a metal or alloy that serves as a filler metal.

The silver brazing alloys (BAg type) and the copper-phosphorus alloys (BCuP type), as described in the preceding sections, are commercially available as sheet, wire, powder or custom-made preforms. The aluminum-silicon brazing alloys (BAlSi type) are available as sheet or wire or as cladding on aluminum brazing sheet.

Preplacing the filler metal in the joint permits close control of the amount of filler metal used, thus avoiding waste, and also helps to obtain uniform filling of a maximum percentage of the joint area. The visible flowing of the preplaced filler metal is also helpful in establishing heating time, or in controlling heating time when manual timing is used.

Instead of preplacing the filler metal in the joint, filler metal can be applied after the joint has been heated to brazing temperature. The filler metal in the form of ribbon, wire or rod is fed to the joint, being drawn into the interface by capillary action. This method is used only rarely in resistance brazing.

The use of special forms of filler metal for resistance brazing is described in four examples in this article and in the article on Brazing of Copper Alloys. In Example 603, one of the workpieces was a copper terminal clad with a 0.003-in.-thick layer of BCuP-5. In Examples 605 and 606, the end of a braided copper conductor cable was "solidified" by dip tinning in BAg-1a and then coined to the desired shape and size, thus providing the filler metal for resistance brazing the end of the cable to a copper or chromium copper terminal. In Example 660, silver plating over an undercoating of plated copper on a high-carbon steel workpiece served as the filler metal for attaching a stranded copper wire by resistance eutectic brazing.

Fluxes and Cleaning

A flux is used in nearly all resistance brazing. It serves the same purposes in resistance brazing as in other brazing processes: providing a coating to prevent or minimize oxidation of the work metal during heating; dissolving oxides that are present or that may form during heating; and assisting the molten filler metal in wetting the work metal to promote capillary flow. However, the flux in resistance brazing has the additional function of serving as an electrical conductor to permit passage of the brazing current through the joint; most dry fluxes are nonconductors and must be mixed with water in order to conduct current.

Application. The flux is usually applied as a dilute water-base paste shortly before the parts and filler metal are assembled for brazing. Arcing and an explosion may occur if the paste is not a thin, uniform layer and free from lumps. If the flux should dry out before brazing is started, it may be possible to restore electrical conductivity by moistening it, but results are not always consistent. Once melted, the flux remains conductive.

If the filler metal is in powder form, flux can be combined with it in a fine-particle-size paste.

Selection. The same fluxes are used for resistance brazing as for other brazing processes on the same work metal, and their selection and properties are described in detail in the article on Torch Brazing and in the articles that describe the brazing of specific types of alloys.

Type 3A fluxes are general-purpose fluxes suitable for most metals that are commonly resistance brazed (although type 4 flux is needed for copper alloys that contain tin, aluminum or silicon); type 1 fluxes are used on aluminum alloy work metals.

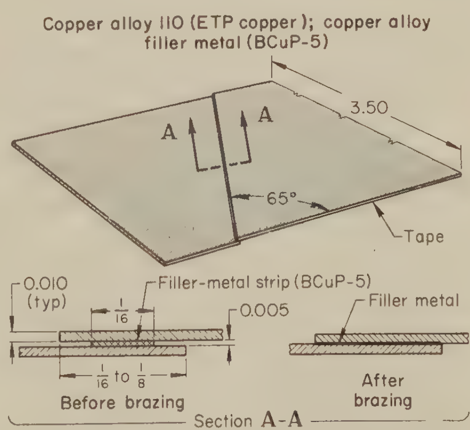
Brazing Without Flux. The two general situations in which a flux is not used in resistance brazing are brazing in a vacuum or a protective reducing-gas atmosphere (see the article on Furnace Brazing), and brazing of copper with a BCuP filler metal.

A flux is not ordinarily needed in resistance brazing of copper when a BCuP filler metal is used, because these filler metals are self-fluxing on copper by virtue of their phosphorus content. However, flux was used in step brazing of copper with BCuP-2 and BCuP-5 filler metals in Example 599.

In some special situations, brazing can be done in air without the use of flux, when brazing is done immediately after cleaning or mechanically abrading the joint surfaces. Special cleanliness of the workpieces made it possible to avoid the use of flux in the automatic resistance brazing of leaded copper alloy parts in Example 602, in which the filler metal was BAg-1.

Cleaning. As in other brazing methods, unless the work metal in the vicinity of the joint is free from grease, oil, dirt and interfering oxide coatings, chemical or mechanical cleaning must be done before resistance brazing, to permit wetting by the molten filler metal and capillary flow.

Removal of flux residues after resistance brazing is ordinarily necessary (as in other brazing processes), and is done by washing in hot water or, if this is not effective, by chemical or mechanical means. Removal of flux residues from braided cable and other parts where crevices are present is especially difficult and not always completely effective.



Machine	Press-type, air-operated, 30-kva resistance welding machine
Loading and unloading	Manual
Filler metal	BCuP-5, 0.005 by 1/16 by 3¾
Flux	None
Electrodes	Electrographite, working surface ¼ by 4 in., 1 in. thick
Heating time	Approx 7½ to 9½ sec
Hold time	12 sec
Timing method	Fixed time (see text)
Joint strength	25,000 psi, min
Joint elongation	10% min

The brazed tape was continuously formed into a 1-in.-diam outer conductor tube for broad-band-transmission ocean cable in lengths of 20 nautical miles (see Example 604 and Fig. 8).

Fig. 4. Lap-joint design using 6-to-12t overlap and 65°-angle sheared ends in resistance brazing 0.010-in.-thick copper tape for subsequent forming into a tube (Example 600)

Joint Design

Joints for resistance brazing are usually lap joints, although other joint arrangements are used where lap joints are not suitable. Workpieces can have a wide variety of configurations, but the joint design must permit contact surfaces, usually flat or conforming, to be pressed together, ordinarily between electrodes, to make the joint.

Special-shape workpieces that are joined by resistance brazing include crossed wires, wires or tubes laid flat against the surface of a second part, stranded or braided wires or cables, shaft ends or collars butt-joined to flanges or rings, armature leads of various shapes inserted into slots in commutator bars, overlapping-spot-brazed flat stock, attachments to the interior of cylindrical shapes or in other types of recesses, and solidified joints of stranded or braided conductor cable to terminals. The wide variety of joint designs for resistance brazing is illustrated in the 16 examples in this article and the article on Brazing of Copper Alloys.

Contact areas of joints for resistance brazing can range from very small to moderately large. A procedure for resistance brazing copper wires only 0.002 to 0.005 in. in diameter to flat terminals is described in Example 603, and resistance lap brazing of ¾-in.-thick copper bars with a contact area of 3 by 4 in. is described in Example 599. Ordinarily, except in multiple-spot brazing (see Example 659), joint contact area is not much larger than that described in Example 599, and joint length is not much greater than joint width on larger parts, because it is difficult to obtain uniform current distribution (and thus, uniform heating) on such large or elongated joint areas. In addition, the capacity of the power source sometimes limits the size of the joint.

Lap joints are preferred to butt joints because they can be made with greater joint strength, as brazed joints are stronger in shear than in tension or bending. In lap joints, overlap should be at least three times the thickness of the thinner member for full joint strength, or at least 1½ times this thickness to avoid a significant loss in electrical conductivity across the joint. In the next example, overlap of 6 to 12 times stock thickness was used to produce strong joints of high conductivity.

Example 600. Design of Lap Joint To Provide Conductivity and Strength (Fig. 4)

Figure 4 shows the design for resistance brazed joints connecting copper tape, 3.5 in. wide by 0.010 in. thick, used for making the outer conductor for broad-band-transmis-

sion ocean cable in lengths of 20 nautical miles. Use of an overlap 6 to 12 times the work-metal thickness provided electrical conductivity across the joint equal to that of the work metal, and helped give joint strength that would withstand subsequent forming of the tape into a tube. The ends of coils of tape 3000 ft long to be joined by brazing were sheared at 65° to its length (instead of 90°) so that the lapped edges of the brazed joint would not be directly opposite each other when the tube was formed (see Fig. 8, page 653).

Flux residues could not be tolerated on the brazed connections, and the manufacturing procedure for the continuous cable did not permit cleaning after brazing. Consequently, BCuP-5, a filler metal that is self-fluxing on copper, was chosen for resistance brazing. Its comparatively low electrical conductivity (10% IACS) was compensated for by the width of the overlap and the low thickness of the layer of filler metal in the completed joint (typically 0.002 in.).

Brazing was done in a 30-kva press-type resistance welding machine fitted with 1-in.-thick rectangular electrographite electrode blocks having a working surface 4 in. long by ¼ in. wide.

The ends of the copper tape were sheared at an angle of 65° (see Fig. 4) and a 1/16-in.-wide strip of filler metal was placed between the overlapping surfaces at the joint. A heating time of 7½ to 9½ sec was used to produce joints having a strength of at least 25,000 psi and elongation of at least 10%. The brazing schedule was established on the basis of destructive testing of brazed joints made at different machine settings.

Where practical, joint design is coordinated with electrode design so as to make the workpieces self-aligning (or, ideally, self-nesting), and thus to minimize the need for special fixtures. Joint design must permit the workpieces to move when the filler metal melts and flows, and should at the same time maintain proper workpiece alignment until the filler metal has solidified completely.

The contacting surfaces of the workpieces must be designed to fit closely together during brazing so as to avoid local overheating, permit capillary action, and minimize voids in the brazed joint. Forming or machining of the areas to be joined is sometimes necessary for proper fit. The design also must permit the application of the electrode force without distortion of the workpieces.

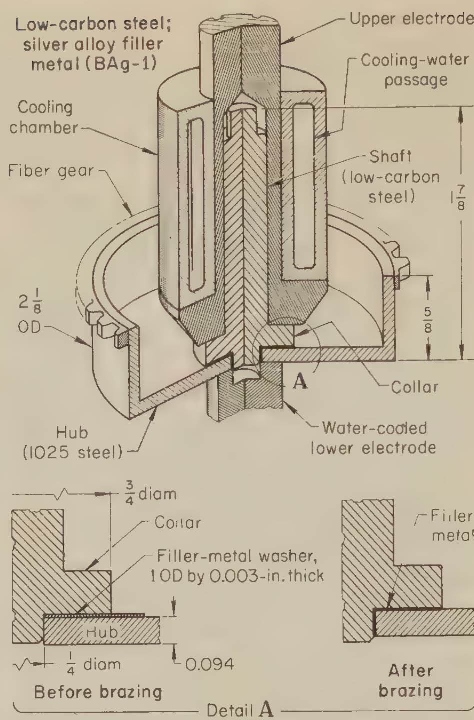
In addition, joint design, in conjunction with electrode design and arrangement, should permit easy assembly of workpieces and filler metal, convenient fluxing (if a flux is used), and easy loading and unloading of the machine.

A variety of joint designs are illustrated in the 16 examples of resistance brazing in this article and in the article on Brazing of Copper Alloys. The various aspects of joint design described in the preceding paragraphs are illustrated in the next example.

Example 601. Design of Workpieces and Electrodes for Self-Fixtured Resistance Brazing (Fig. 5)

In resistance brazing a 0.094-in.-thick 1025 steel hub to a 3/8-in.-diam low-carbon steel shaft in a press-type resistance welding machine, the workpieces and the electrodes were designed for self-fixturing, as shown in Fig. 5.

Resistance brazing was the only available method suitable for joining parts of the exact design shown in Fig. 5, because of the need to avoid heat damage to the fiber



Machine ....Press-type, air-operated, 50-kva resistance welding machine, rated at 80 strokes per hour
Loading and unloading ....Manual
Filler metal ....BAg-1 preform washer, 0.003 in. thick by 1-in. OD
Flux ....Type 3A water-base paste
Electrodes:
Upper ....RWMA class 2 (chromium copper), 1 3/16-in.-diam, class 14 (molybdenum) facing, water cooled, recessed to hold shaft (see illustration)
Lower ......RWMA class 2 (chromium copper), 9/16-in.-diam, water cooled, recessed to hold pilot tip of shaft
Timing method ....Electronic
Production rate ....80 assemblies per hour

Fig. 5. Shaft-and-hub assembly for which workpieces and electrodes were designed for self-fixtured resistance brazing. Heat input was controlled and localized to avoid damaging the fiber gear that was bonded to the periphery of the hub. (Example 601)

gear. If redesign of the shaft for annular projection welding had been permissible, that method would also have been suitable.

For joint strength, the shaft had a collar to provide a flat annular contact surface with an ID of ¼ in. and an OD of ¾ in. The ¼-in.-diam chamfered locating tip on the bottom of the shaft extended through the clearance hole (diametral clearance of 1/32 in.) in the hub and projected about 0.015 in. into a clearance recess (diametral clearance of 1/32 in.) in the lower electrode.

The flat upper surface of the collar on the shaft provided an annular contact surface for the upper electrode, and the upper portion of the shaft fit into a clearance hole (diametral clearance of 1/32 in.) in the upper electrode.

In preparing the assembly for brazing, the operator first applied a water-base paste of type 3A flux to the shaft by dipping, and then slipped a washer of BAg-1 filler metal and the hub over the locating lower tip of the shaft, fitting them against the lower surface of the collar. Then, holding the assembly in an upright position by the hub, the operator inserted the shaft into the recess in the upper electrode and lowered the upper electrode at a controlled rate until the electrodes were closed on the assembly at low pressure. Pushing the start switch on the welding machine actuated the brazing force and current, and the brazing sequence was completed automatically.

The press-type resistance welding machine was air operated and was rated at 50 kva and for operation at 80 strokes per hour. The specially designed upper electrode had a class 14 (molybdenum) facing on a class 2 (chromium copper) shaft; the lower electrode was class 2 (chromium copper). Both electrodes were water cooled.

If the flux dried out before the assembly could be brazed, dipping the assembly in water restored the conductivity of the flux so that the brazing current could be passed through the joint.

Advantages of resistance brazing in this application were (*a*) the convenience of providing localized and controlled heat input to avoid damaging the fiber gear bonded to the periphery of the hub (see Fig. 5); (*b*) the simplicity and ready availability of the equipment; and (*c*) the low level of required operator skill.

Production rate for resistance brazing this assembly was about 80 assemblies per hour. Additional details of equipment and operation are given with Fig. 5.

Resistance Brazing as a High-Production Process

Most resistance brazing is done with resistance welding equipment, which is readily adapted for mechanized production of intermediate or large quantities of resistance brazed assemblies. Example 603 describes fully mechanized (including loading and unloading) high-speed mass-production resistance brazing of copper wires to terminals in a ferrite-core storage frame used in a computer.

All operations except loading and unloading were done automatically in mass production in several other examples in this article and in the article on Brazing of Copper Alloys, including Examples 597, 602 and 660. Resistance brazing of intermediate quantities was done semiautomatically in Examples 598 and 600, and manually in Example 658.

In Example 658, a total of 100,000 resistance brazed connections were made annually, using a portable resistance welding machine and hand-held tongs. In Example 598, intermediate quantities of cross-wire connections were made semiautomatically, using a traveling bench-mounted portable welding head in a resistance brazing operation that was integrated with other assembly operations in a mechanized coil-winding machine. In Example 600, the ends of coils of copper strip or tape were semiautomatically joined by resistance brazing as part of the continuous fabrication of 20-nautical-mile lengths of ocean cable.

Special Techniques Used in Resistance Brazing

Characteristics common to nearly all resistance brazing operations include the following: (*a*) the use of filler metal, (*b*) localized heat input, (*c*) passage of the heating current through the joint, which is held together under pressure, and (*d*) use of standard or modified resistance welding machines.

In most other respects, as the examples show, resistance brazing applications vary widely. They range from the simplest manual operations on small quantities of noncritical parts to fully mechanized high-speed mass-production of brazed assemblies to rigid standards. Workpieces vary widely in size, shape, and type and condition of

material, and special techniques and procedures often are needed.

The application of a number of special techniques to resistance brazing is described in the following sections.

Step brazing involves making two or more brazed joints in succession on the same assembly, using filler metals that have progressively lower working-temperature ranges, and is conveniently done by resistance brazing, in which the heat input is localized and can be controlled accurately. Step brazing is used extensively in making circuit breakers and other types of electrical switchgear and power distribution equipment; Example 599 describes step brazing a circuit-breaker subassembly.

Use of Fast Follow-Up. The inertia of the moving mass of the electrode holder and electrode can prevent electrodes and workpieces from responding quickly enough to the melting of the filler metal, especially when small parts are being brazed. The delayed response and rebound of the electrode holder and the workpieces can then cause expulsion of too much of the filler metal, producing a weak brazed joint bonded over only a small percentage of its area.

Fast follow-up is especially important in resistance brazing with filler metals (such as BAg-1 and BAg-1a; see Table 1 on page 686 in the article on Brazing of Copper Alloys) that flow at a temperature only 15 to 20 degrees above the temperature at which they start to melt. For applications using such filler metals, resistance welding machines are equipped with special low-inertia, low-friction electrode holders that permit rapid follow-up by the electrode when the filler metal flows.

One type of low-inertia welding head is described in the article on Projection Welding and is illustrated in Fig. 5 on page 437 in that article. A specially designed spring-loaded decoupling system was used in a gravity-operated brazing head in Example 603 for resistance brazing copper wires to terminals. In the example that follows, a spring-loaded fast-follow-up electrode holder was used in an air-operated automatic resistance welding machine in brazing a post-and-flange assembly.

Example 602. Use of a Low-Inertia Upper-Electrode Holder for Fast Follow-Up in Automatic Resistance Brazing (Fig. 6)

The binding post and flange shown in Fig. 6 were resistance brazed with BAg-1 filler metal (solidus of 1125 F; liquidus of 1145 F), used as a preformed ring. Because of the short time interval between melting and flowing of this filler metal, a special low-inertia, low-friction upper-electrode holder was used to provide fast follow-up and to minimize rebound. The spring-controlled action of this electrode holder kept the two workpieces in intimate contact with the filler metal throughout the melting-and-flowing sequence, and resulted in the proper capillary action and maximum filling of the brazed joint.

Brazing was done on a 75-kva automatic resistance welding machine with a 440-v input, a 4-to-7.33-v output, and synchronous controls. A hollow lower electrode was shaped to hold the post. The filler-metal preform and the flange rested on the collar of the binding post (see Fig. 6). The upper electrode was ⅝ in. in diameter and was flat. Both electrodes were of RWMA class 2 material (chromium copper).

The procedure was as follows: The two parts were cleaned by acid dipping and were assembled with a preform of 0.032-in.-diam BAg-1 wire. The assembly, which was self-fixturing, was mounted by hand in the lower electrode. Force, voltage and time were controlled automatically. The assembly was clamped with a force of 190 lb and heated with a secondary voltage of 6.9 v for 27 cycles, or a little less than half a second.

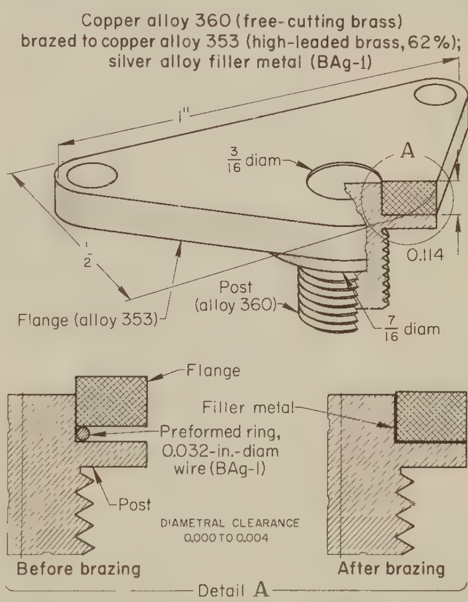
It was necessary for the flange to bottom on the shoulder of the binding post and be perpendicular to it within one degree. The filler metal was required to show on the lower side of the flange all the way around the joint. Production rate was 278 assemblies per hour. Production costs are given in the table that accompanies Fig. 6.

Electrode cost per assembly was negligible, and the job was done on a machine that had already been amortized. Equipment details and conditions for brazing also are given in the table with Fig. 6.

The post was made of copper alloy 360, and the flange, of copper alloy 353. Arc or resistance welding processes are not ordinarily suitable for joining leaded brasses of such high lead content (nominally 2% for alloy 353, and 3% for alloy 360), because the low-melting lead concentrates in the grain boundaries during exposure to welding temperatures, causing cracking and weakening of the joints. With the use of resistance brazing, and a small and closely controlled heat input, these difficulties were avoided.

The heat for brazing was generated chiefly in the filler metal and the regions of the workpieces in the immediate vicinity of the joint. Electrical conductivities of the materials involved were as follows, expressed in per cent IACS: RWMA class 2 electrodes, 75 minimum; BAg-1 filler metal, 28; copper alloy 360 (post), 26; and copper alloy 353 (flange), 26. The use of class 2 electrodes for this operation allowed localization of heating in the joint and use of a low total heat input.

Resistance brazing was preferred to torch brazing because of better controllability of heat input, greater speed and lower operator-skill requirements, and was preferred to induction brazing because of the higher cost of equipment for induction brazing and the availability of resistance welding equipment in the plant.



Machine	Press-type, air-operated, 75-kva automatic resistance welding machine, synchronous controls, equipped for fast follow-up (see text)
Loading and unloading	Manual
Filler metal	Preformed ring of 0.032-in.-diam BAg-1 wire
Flux	None
Precleaning	Acid dip both parts
Electrodes	RWMA class 2 (chromium copper), ⅝-in. diam(a)
Electrode force	190 lb
Brazing voltage	6.9 v
Heating time	27 cycles
Production rate	278 assemblies per hour

Production Cost per Assembly

Labor (1 operator at $3.36 per hour)	$0.0121
Filler metal (at 35¢ per 100 assemblies)	0.0035
Power (at 1.5¢ per kwhr)	0.000094(b)
Electrodes	Negligible
Machine	0.00(c)
Total	$0.0157

(a) Upper electrode had a flat face; lower electrode was recessed to hold post. (b) Based on consumption of 50 kwhr per brazed joint. (c) The machine had already been amortized.

Fig. 6. Post-and-flange assembly that was automatic resistance brazed with BAg-1 filler metal using a special low-inertia upper-electrode holder for fast follow-up (Example 602)

Brazing Plastic-Coated Wire. Organic coatings, grease, oil, oxides and other types of nonmetallic materials must ordinarily be removed from the contact surfaces of workpieces to be resistance brazed, to permit wetting of the entire joint area by the molten filler metal. Some types of organic coatings, however, can be removed readily and completely by electrode heat and pressure as part of the brazing sequence.

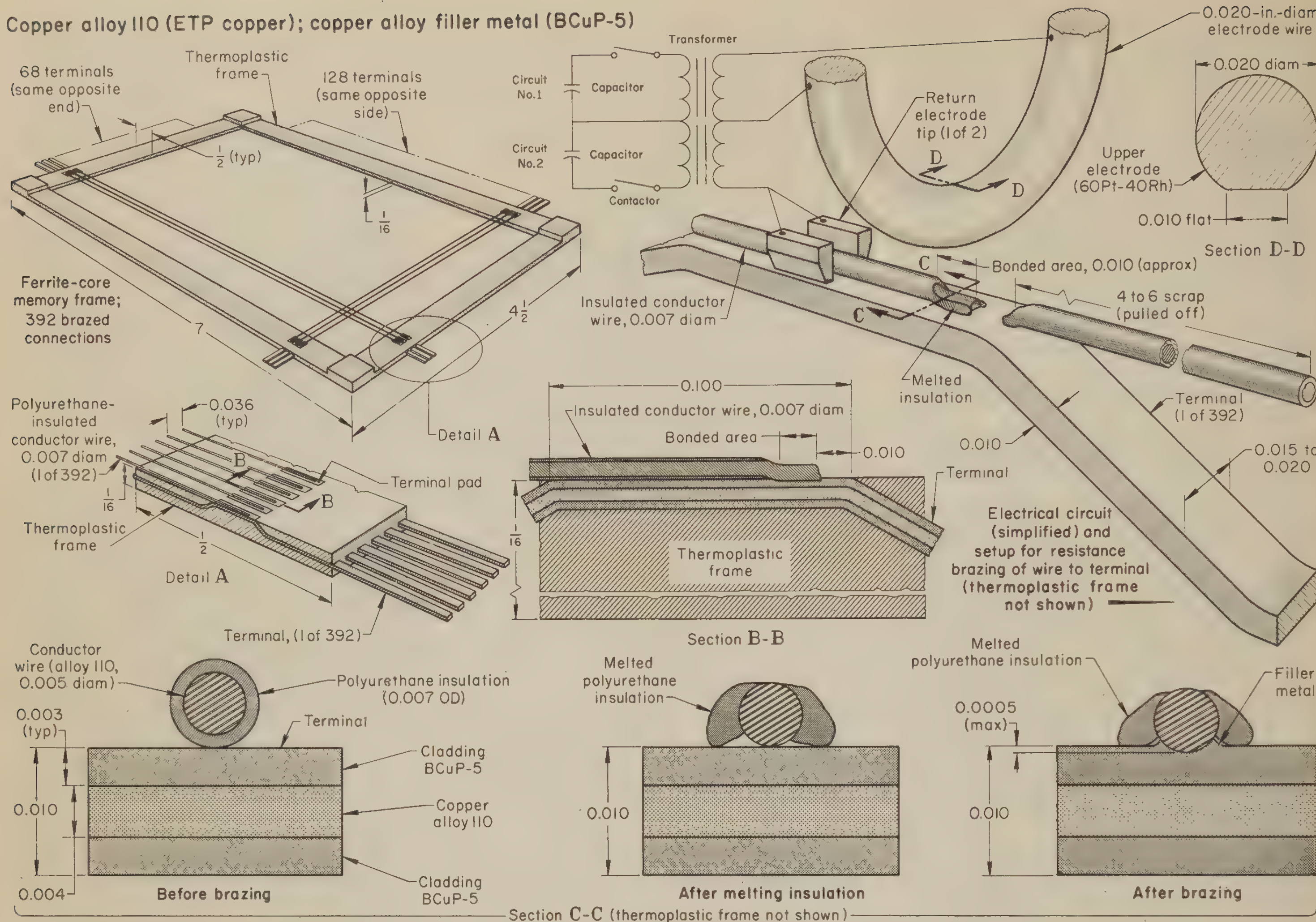
In the example that follows, a special energy-supply system and a dual electrical circuit were used (*a*) to remove polyurethane insulation from copper wire with the electrode, (*b*) to braze the stripped wire to a terminal, and (*c*) to burn off residues from the electrode after brazing each joint. The brazing electrode was made of a precious metal alloy to withstand this heating sequence and to resist alloying with copper or the BCuP-5 filler metal that was used. In addition, fast follow-up was provided by a specially designed spring-loaded decoupling system in a gravity-operated brazing head.

Example 603. Use of Capacitor-Discharge Energy Pulses To Remove Insulation and Resistance Braze (Fig. 7)

Resistance heating of the brazing electrode by a preliminary capacitor-discharge energy pulse was used to melt and strip insulation from the contact surfaces of polyurethane-coated copper wires in resistance brazing them to terminal pads in a ferrite-core storage unit for a computer (see Fig. 7). An energy pulse from a capacitor was also passed through the retracted electrode between brazing operations to burn residual insulation material from the electrode tip. The brazing electrode was made of 60Pt-40Rh to withstand a temperature of 1700 F in continuous high-speed production and to resist alloying with copper or filler metal. Fig. 7 (view at upper left) shows the general construction of a single "two-dimensional" ferrite-core memory frame, and detail A is an enlarged view of a portion of the frame.

The copper conductor of the wires was 0.005 in. in diameter (other conductor sizes, down to 0.002 in. in diameter, were used in other frames of this type), and the over-all diameter for the wire shown, including the insulation, was about 0.007 in. The terminals were punched from 0.004-in.-thick copper strip clad on both sides with a 0.003-in.-thick layer of BCuP-5 brazing filler metal. (Section C-C, bottom left, Fig. 7, shows a conductor wire and terminal.)

The terminals were encased in the thermoplastic frame, with their outer contact fingers extending from the sides of the frame, and the terminal pads embedded



Machine	Bench-mounted capacitor-discharge resistance welding machine (see text)	Filler metal	0.003-in.-thick BCuP-5 cladding on terminals	Electrode force	100 grams (weight)
Capacitance and voltage of power supplies (capacitors):		Precleaning	None	Electrode-head mass	20 grams
Circuit No. 1	735 mfd, approx 128 v	Brazing electrode	0.120-in.-radius loop of 0.020-in.-diam 60Pt-40Rh wire with a 0.010-in. flat honed on bottom surface	Energy and duration of pulses(a) for:	
Circuit No. 2	735 mfd, approx 82 v	Return electrodes	Beryllium copper shoes	Wire stripping	5-7 watt-sec, 2-3 millisec
Flux	None			Brazing	2-3 watt-sec, 2-3 millisec
				Electrode cleaning	5-7 watt-sec, 2-3 millisec
				Postbraze cleaning	None

(a) Data are approximate values for wire with conductor diameter of 0.002 to 0.005 in.

Fig. 7. Ferrite-core memory frame for a computer, in which 392 connections were made by capacitor-discharge resistance brazing, in the setup shown. Pulsed energy from capacitors was used to melt the polyurethane insulation from the wire during brazing and to burn residues off the 60Pt-40Rh electrode tip between brazing operations. (Example 603)

flush with the surface of the frame. Locally stripped contact surfaces of the wires were brazed to the terminal pads, and the scrap ends of the wires were then broken away, leaving the brazed assembly shown in the over-all and detail views in Fig. 7.

Circuit. The brazing setup and the circuit are shown schematically at the upper right in Fig. 7. The gravity-loaded resistance brazing tip was a loop of 0.020-in.-diam 60Pt-40Rh wire with a 0.010-in.-wide flat (section D-D, Fig. 7) honed on the bottom to provide the contact surface. The tip was percussion welded to the 0.040-in.-diam copper electrode shanks, as described in Example 177 in the article on Percussion Welding. The spring-loaded return electrode, which had two tips that contacted the terminal pad on each side of the wire and 0.010 to 0.030 in. behind the brazing tip, was made of beryllium copper. The small controlled amounts of resistive heat needed for brazing were supplied by the discharge of capacitors that were automatically recharged by rectifiers (not shown in Fig. 7) immediately before each energy pulse.

Brazing Procedure. The wire leads, held by scrap ends extending 4 to 6 in. beyond the edges of the frame, were laid across the terminal pads, and the brazing electrode was pressed down on each of them in turn. To melt the polyurethane insulation, the switch was closed in the circuit identified in Fig. 7, top center, as circuit No. 1. This passed a current through the loop-shape brazing electrode, producing enough heat to break down and strip the insulation (section C-C, bottom center). Electrical contact was thus firmly established between the brazing electrode and the wire lead and between the lead and the terminal. To initiate brazing, the switch in circuit No. 2 was closed, causing a pulse of current to flow from the electrode through the wire and terminal and back through the return electrode. This pulse generated enough heat at the wire-terminal interface to melt the filler metal at the contact area to a depth of about 0.0005 in. and produce a fillet on each side of the wire (Fig. 7, section C-C, bottom right).

The brazing electrode was cleaned before each braze by pulsing current through the tip (circuit No. 1 in Fig. 7) to vaporize polyurethane residues. Timing of the entire sequence of operations was done with a solid-state timing device.

Additional equipment details and brazing conditions are given in the table with Fig. 7.

Design for Fast Follow-Up. The sudden melting of the filler metal was too rapid for a conventionally mounted welding head to follow. The electrode mass was made as low as possible and the electrode was decoupled from the applied weight by a spring so that it could follow rapidly the collapse of the filler metal, thus avoiding rebound, expulsion of molten filler metal, and destructive arcing.

Testing of Joints. The removal of the scrap ends of the wires, which was done manually, provided a test of the joint strength. On properly brazed joints, the strength of the joint was greater than the tensile strength of the wires, and the scrap end broke away, leaving the joint intact (Fig. 7, upper right and section B-B).

The operator usually peeled away the scrap ends in clusters, pulling in a direction away from the free end of the wire.

Process reliability was about 99.7%. Over a period of several years of mass-production use of this joining procedure, none of the brazed joints failed in service.

Alternative Methods. Previously, these assemblies had been joined by wrapping the wire around terminals designed for the purpose and dip soldering the assembly in molten tin-lead solder. The molten metal

removed the plastic insulation and fused the joints. However, heat from the molten bath often damaged the assembly, the process was difficult to automate, dip soldering did not lend itself to high-density packing, the assembly had to be fluxed, and subsequent cleaning was difficult.

Preventing Overheating. One technique used in resistance brazing to prevent overheating of the workpiece is the use of pulsed current. In Example 656 in the article on Brazing of Copper Alloys, six pulses of 11 cycles heat time and eight cycles cool time were used to heat the joint to brazing temperature in attaching copper leads to a copper commutator bar without significant annealing of the commutator bar.

A single energy pulse from a capacitor was used in Example 603 in this article to provide the small, closely controlled, rapid heat input needed to resistance braze copper wires 0.002 to 0.005 in. in diameter to flat terminals.

In Example 598, the cross-wire joint and precision timing and current control were the major factors in limiting the heat input to the work; and in Example 602, joint design and the relative electrical conductivities of the electrodes, work and filler metals made possible highly localized heating and the use of low total heat input.

In Example 659 in the article on Brazing of Copper Alloys, successive overlapping spot brazing was used to prevent overheating in resistance brazing copper strip to copper bus bar with a total joint area 4 in. wide by 8 in. long. In the example that follows, small overlapping spot brazes were also used to avoid annealing of adjacent high-carbon steel wires in resistance brazing of repair patches to the copper inner conductor tube of ocean cable.

Example 604. Use of Overlapping Spot Resistance Brazing To Attach Repair Patches to Copper Tube (Fig. 8)

Weld defects or unwelded sections ("weld skips") in the seam welded inner conductor tubes of broad-band-transmission ocean cable were repaired by resistance brazing patches over the defects or unwelded sections, as shown in Fig. 8.

Cable Manufacture. The ocean cable was made in a process that was operated continuously for over 80 hr to produce a section of cable 20 nautical miles long. The core, which was the strength member of the cable, consisted of 41 high-carbon steel wires of five different sizes stranded in a tubular strander, in a pattern designed for maximum strength, and dimensioned in a closing die to a 0.290-in. outside diameter.

The inner conductor was formed around the steel core into a 0.5-in.-diam tube from 0.023-in.-thick copper alloy 102 (OF copper) strip, and was then gas tungsten-arc seam welded, reduced in diameter in a series of reducing rolls to fit tightly around the steel wire, and drawn through a final die to dimension it and to force some of the copper into the interstices of the stranded steel core.

Subsequent steps in the manufacture of the cable were: continuous extrusion of low-density polyethylene around the inner conductor, forming of the copper outer conductor into a tube around the polyethylene dielectric layer (see Example 600 for resistance brazing of copper strip to make the outer conductor), and extrusion of the outer sheath of black ethylene plastic.

Defects in Inner Conductor. Pinholes, weak spots and "weld skips" in the seam of the inner conductor generally originated with defects or irregularities in the copper strip. The seam was visually inspected for flaws and continuously checked for weld skips by a "seam integrity tester" after welding, and was tested again in the same way after final sizing of the inner conductor. The tester consisted of a bridge circuit in which two coils surrounded the inner conductor and formed two legs of the bridge. When a weld skip passed through the first coil, the bridge became unbalanced, triggering an alarm. A skip 1⁄32 in. or more in length could be detected.

It was important to detect weaknesses or weld skips before proceeding to subsequent operations. The extrusion process built up considerable pressure in trapped air inside the welded inner conductor because of the heat generated and the choking effect of the 20-nautical-mile length. Where there were flaws or skips in the welding of the inner conductor, this compressed air blew bubbles in the extruded polyethylene, creating voids in the dielectric and impairing the electrical function of the cable. Defects that were not detected and repaired before extrusion of the inner dielectric could necessitate repair or removal of the defective section of cable later in the manufacturing process, with greater difficulty and cost.

Only four repairs of any kind were permitted in a 20-nautical-mile length of cable. The average number of inner-conductor repairs per cable length was 2.3. Reliability of these resistance brazed patch repairs was 98%. The repaired seam had to be capable of withstanding more than 80 psi air pressure after the inner conductor had been subjected to 50 reverse bends over a 3-ft radius.

Repair Technique. Finding a technique for repairing defects in the inner-conductor seam was complicated by the need for a ductile patch and by the fact that excessive heat might anneal the steel core wires and thus weaken the cable unacceptably.

Techniques that were tried and found unsatisfactory used tin-lead solder patches, epoxy patches and resistance welded gold-plated copper patches; the last method overheated the steel core wires.

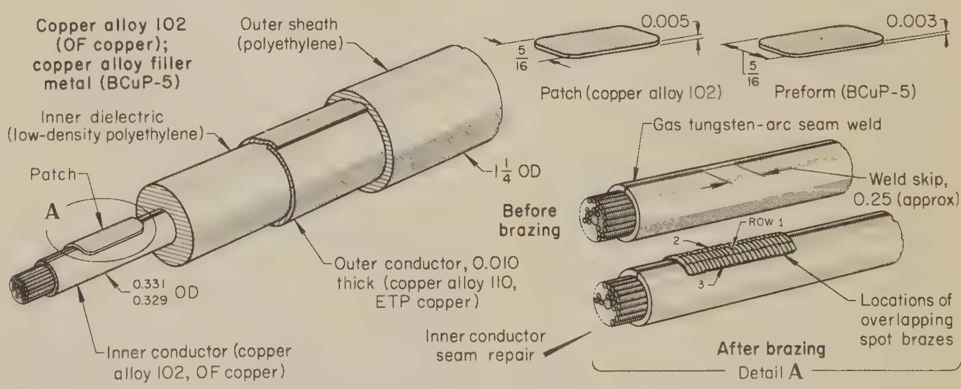
The technique that was finally adopted consisted of resistance brazing 0.005-in.-thick copper alloy 102 patches over the defects, using 0.003-in.-thick strips of BCuP-5 filler metal and a resistance welding machine. A strip of filler metal and a copper patch, each 5⁄16 in. wide and of a suitable length, were placed over each defect (see Fig. 8). Then the patch was stitched all over with overlapping spot brazes, making one braze at a time. The individual spot brazes were about 1⁄8 by 3⁄16 in., and were spaced on 0.030 to 0.040-in. centers, as shown in Fig. 8. Afterward, the patch was smoothed with emery paper to keep the diameter of the inner conductor from exceeding 0.333 in., and was polished with crocus cloth.

The electrode tips were machined to conform to the curvature of the inner conductor. Both electrodes were made of 5⁄8-in.-diam class 1 material (cadmium copper) faced with class 12 material (copper-tungsten). The upper electrode had a groove with a 0.167-in. radius and the face was reduced to 1⁄8 in. wide. The lower electrode also had a groove with a 0.167-in. radius, but the face was not reduced in width, and thus provided maximum support for the conductor and a large contact area.

Brazing force was 100 lb, and the current and heating time were selected to provide just enough heat to melt the brazing filler metal completely. Additional equipment details and brazing conditions are given in the table that accompanies Fig. 8.

Solidified Joints. Resistance brazing is frequently used to join braided or stranded electrical conductors, especially in the larger sizes (rated to carry currents of about 60 amp or more), to each other or to other types of conductors. Braided conductors of smaller sizes are conveniently joined by resistance welding, thus avoiding the use of filler metal and flux, as in Example 420 in the article on Resistance Welding of Copper Alloys. However, the currents needed for resistance welding of heavy braided or stranded conductors are prohibitively high, and conductor cables rated for 60 amp or more are more conveniently joined by resistance brazing of solidified joints.

This type of joint has better resistance to corrosion than mechanically crimped connectors and has the additional advantage that it can be machined and formed much like a single continuous piece of metal. As shown in

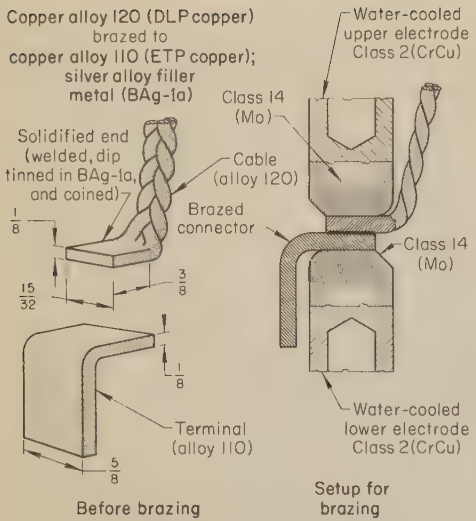


Machine .... Portable resistance welding machine, 50 kva	Electrode force .... 100 lb
Welding head .... (a)	Method of applying force .... Air
Filler metal ... BCuP-5, 0.003 by 5⁄16 wide, length to suit defect length	Brazing current .... 50,000 amp (typical)
Flux .... None	Brazing voltage (open circuit) .... 30 v
Precleaning .... Wipe with trichlorethylene	Heating time .... 2 cycles
Electrodes .... (b)	Hold time .... 30 cycles (typical)
	Timing method .... Electronic
	Joint reliability 98%

(a) Mounted in fixed ways; upper-electrode holder, cantilever mounted; lower-electrode holder, stationary. (b) Class 1 (cadmium copper), 5⁄8-in. diam, with class 12 (copper-tungsten) conforming tips.

In making the repair, overlapping spot brazes about 1⁄8 in. wide by 3⁄16 in. long and spaced on 0.030 to 0.040-in. centers were made one-at-a-time in three rows, as shown in Detail A, between opposing electrodes, the tips of which conformed to the curvature of the workpiece. The lower electrode had a much larger contact area than the upper electrode, so that it functioned only as a return electrode.

Fig. 8. Ocean cable that was made in continuous production in lengths of 20 nautical miles, and copper alloy patch that was overlapping-spot resistance brazed to the copper alloy inner conductor tube to repair gas tungsten-arc seam welding defects in the tube (Example 604)



Machine	Press-type 75-kva resistance welding machine, bench mounted, air operated, with automatic timing
Loading and unloading	Manual
Filler metal	BAg-1a(a)
Flux	AWS type 3A
Precleaning	Terminals degreased and bright dipped
Electrodes	RWMA class 2 (chromium copper) with ½-by-⅜-in. class 14 (molybdenum) facing, water cooled; see illustration
Electrode force	350 lb
Brazing current	15,000 amp
Heating time	5 sec
Hold time	20 cycles
Post treatment	Water quenching(b)
Production rate	250 assemblies per hour

(a) Filler metal was applied to the end of the braided cable by dip tinning to produce a solidified end. (b) Assemblies were dropped into cold running water immediately after brazing.

Fig. 9. Solidified end of a 60-amp braided DLP copper conductor cable and ETP copper terminal that were resistance brazed using molybdenum-face copper alloy electrodes to permit short heating time (Example 605)

Examples 605 and 606, the solidified end of the braided or stranded cable provides the filler metal for resistance brazing. Where the shapes of the cable and the other workpiece permit, solidification and brazing can be done simultaneously to minimize exposure to heating.

In the two examples that follow, the ends of braided conductor cables were joined to other types of workpieces by resistance brazing. The end of the braided cable first was resistance welded using class 14 (molybdenum) electrodes to fuse the strands partially and to consolidate the braid. It was then dip tinned with BAg-1a brazing filler metal, coined to the desired shape and size, and finally resistance brazed to a solid terminal or other workpiece.

Example 605. Use of Molybdenum-Faced Electrodes To Permit Short Heating Time in Brazing a Solidified Joint (Fig. 9)

In resistance brazing the solidified end of a 60-amp braided copper conductor cable to a copper terminal, the heating time had to be minimized to avoid excessive annealing of the terminal and excessive penetration of filler metal into the braided cable.

By using water-cooled class 2 (chromium copper) electrodes with a class 14 (molybdenum) facing, the joint was made with a heating time of 5 sec. The braided cable, with its resistance welded, dip tinned and coined solidified end, and the terminal are shown at the left in Fig. 9. The completed assembly, ready for unloading, is shown between the electrodes at the right in Fig. 9.

A bench-mounted resistance welding machine was used. Timing of the brazing sequence was automatic. The production rate for brazing was 250 assemblies per hour. Equipment details and brazing conditions are given in the table with Fig. 9.

Carbon electrodes, simpler to prepare and less expensive than high-resistivity metallic electrodes, often are used in short-run resistance brazing applications, where their low resistance to wear is not important. If heat input to the joint is not critical, manual timing also can be used, as in this example:

Example 606. Use of Carbon Electrodes and Manual Timing in Short-Run Brazing of a Solidified Joint (Fig. 10)

Carbon electrodes, which are simpler to prepare and less expensive than molybdenum-faced copper alloy electrodes, were used for joining small quantities of alloy 184 (chromium copper) bolt heads to flat braided 100-amp copper alloy 120 conductor cable, as shown in Fig. 10. Heat input to the joint was less critical in this application than in the one described in Example 605, and manual timing was used.

A specially designed bench-mounted manual press-type resistance welding machine rated at 50 kva was used. Application of the brazing current was manually controlled by the operator by means of a foot switch that operated a magnetic contactor. The operator observed the joint while the current was applied and released the switch to shut off the current when the filler metal was seen to flow. Force was applied by deadweights on the ram. The electrodes, normally closed, were opened by foot pedal to insert or remove assemblies.

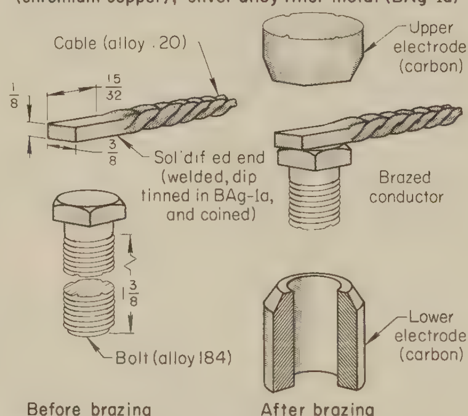
The carbon electrodes used were a medium-hard grade of carbon-graphite that had a resistivity of 0.0005 ohm-in.

In preparation for brazing, the bolt was degreased. The end of the braided cable was resistance welded using class 14 (molybdenum) electrodes to partially fuse the strands and consolidate the braid, and then was dip tinned with BAg-1a brazing filler metal and coined to shape and size.

The bolt and the solidified end of the cable were assembled between the carbon electrodes, as shown in Fig. 10, and were resistance brazed. The assembly was held clamped between the electrodes until the operator observed solidification of the filler metal. Then the electrodes were manually opened and the assembly was removed and dropped into cold running water.

By use of this procedure, brazed joints having good strength and electrical conductivity were produced simply, and at low cost and without excessive annealing or softening of the chromium copper bolt head. Additional equipment details and brazing conditions are given with Fig. 10.

Copper alloy 120 (DLP copper) brazed to copper alloy 184 (chromium copper); silver alloy filler metal (BAg-1a)



Machine	Press-type manual resistance welding machine, bench mounted, 50 kva (see text)
Loading and unloading	Manual
Filler metal	BAg-1a(a)
Flux	AWS type 3A, diluted with water
Precleaning	Degrease bolt
Electrodes	(b)
Electrode-face dimensions:	
Upper	½ by ⅜ in.
Lower	¾-in.-OD annulus (see illustration)
Electrode force	40 lb(c)
Brazing current	1800 amp
Heating time	20 sec, approx(d)
Hold time	4 sec, approx(e)
Post treatment	Water quench(f)

(a) Filler metal was applied to the end of the braided cable by dip tinning to produce a solidified end. (b) Carbon-graphite, medium hard, 1-in. diam; mounted in class 2 (chromium copper) water-cooled holders (not shown). (c) Applied by deadweights on ram. (d) Heating was terminated by operator when flow of filler metal was observed. (e) Load was released by operator when solidification was observed. (f) The completed assemblies were dropped into cold running water immediately after brazing.

Fig. 10. Solidified end of flat braided DLP copper conductor cable and chromium-copper bolt head that were joined by resistance brazing using carbon electrodes and manual timing (Example 606)

Alloy (Eutectic) Brazing. Because resistance brazing in a resistance welding machine offers localized, controlled heat input to the joint and controlled application of brazing force, it is well suited for alloy, or eutectic, brazing.

Example 660 in the article on Brazing of Copper Alloys describes resistance eutectic brazing of copper wire to high-carbon steel that previously had been plated with an undercoat of copper and then with silver.

Resistance brazing with carbon electrodes has been used to join EC aluminum workpieces with copper-foil filler metal 0.001 to 0.005 in. thick. The pressure on the contact area of the workpieces was maintained at 1200 to 2000 psi. Current densities of 2500 to 4000 amp per square inch and heating times of 3 to 60 sec (depending on the foil thickness and joint area) were used for complete fusion of the copper. No flux was used, and the workpieces were precleaned by vapor degreasing.

All of the copper filler metal alloyed with the aluminum work metal to form a molten phase, most of which was squeezed out of the joint. The brazed joints, including butt joints, had electrical conductivity essentially the same as that of the work metal. [For additional information and references on this technique, see Kent R. Van Horn, Ed., "Aluminum", Vol. III, p 510-511 (ASM, 1967), and James R. Terrill, *Welding Journal,* Sept 1962, p 799-804.]

Other Examples of Resistance Brazing, Presented in the Article "Brazing of Copper and Copper Alloys", Pages 685 to 702

Example 655: ETP copper stranded conductor wire joined to silver-plated ETP copper ring
Example 656: ETP copper armature leads assembled to silver-bearing TP copper commutator bars
Example 657: OF copper armature leads brazed to ETP copper bars
Example 658: Strip-type connectors joined to terminals on large apparatus; ETP copper connectors and terminals
Example 659: ETP copper terminals assembled by manual multiple-spot brazing
Example 660: ETP braided copper wire brazed to high-carbon steel spring plated with silver over copper; the plating served as brazing filler metal.

Dip Brazing of Steel in Molten Salt

*By the ASM Committee on Brazing of Steel**

DIP BRAZING in molten salt, also called salt bath brazing and molten chemical-bath dip brazing, is a process in which the assembly to be brazed is immersed in a bath of molten salt, which provides the heat and may provide the fluxing action for brazing. The bath temperature is maintained above the liquidus of the filler metal but below the melting range of the base metal. This article describes the application of dip brazing to carbon and low-alloy steels with silver alloy, copper-zinc alloy, and copper filler metals. For information on dip brazing of cast iron, stainless steel, aluminum alloys and copper alloys, see the articles on pages 660 to 702 in this volume.

Advantages of salt bath brazing include the following:

1. Time for heating is about one-fourth that required in a controlled-atmosphere furnace.
2. A protruding joint can be selectively brazed by partially immersing the assembly.
3. A cocoon of frozen salt forms instantly around the cold assembly when it is immersed in the molten salt, and this usually prevents premature melting of the brazing filler metal by providing a temporary insulator.
4. By selection of an appropriate salt composition, it is often possible to combine heating and fluxing of the work in a single step, although flux can be applied to the joint and dried before brazing.
5. Brazing can usually be combined with carburizing or hardening, without the necessity for a separate reheating operation.
6. More than one assembly can be brazed at the same time, production being limited only by the size and heating capacity of the furnace. Also, several joints in an assembly can be brazed at the same time.
7. The workpiece is protected from scaling or decarburization by a thin film of salt that adheres to the surface of the assembly when it is removed from the salt bath.
8. Removal of the salt film is accomplished by dissolving during quenching or washing operations. When flux is used, there is no removal problem; flux is either dissipated during the brazing operation or dissolved simultaneously with the salt film during washing.
9. The density of the molten salt supports a considerable portion of the weight of the workpiece so that, in effect, the assembly weighs less when immersed, which can reduce the likelihood of distortion during heating.

Limitations of salt bath brazing include the following:

1. The process is not generally used for intermittent operation, being better suited for work that requires daily production.
2. Joints that do not protrude from the assembly cannot be selectively brazed by partial immersion; most or all of the assembly must be heated to the brazing temperature in order to braze such joints.
3. The workpieces must be dry and free of all moisture, because the molten salt reacts violently with moisture and will spatter and may even explode. It is necessary to preheat all work if moisture is present.
4. Buoyant parts are difficult to braze in a salt bath because they cannot be easily submerged.
5. The shape of the part must be such that it will not trap air or salt and will drain completely after removal from the salt bath.
6. The assemblies should not require large, complicated fixtures.

Furnaces

A salt bath furnace consists essentially of a metal or ceramic (refractory) pot that serves as a container for the molten salt. Some salt bath furnaces are externally heated by gas, oil, or electrical resistance; this type of furnace lends itself more readily to intermittent operation, and is not widely used for high-volume production. On the other hand, furnaces internally heated by immersed or submerged electrodes are not well suited to intermittent operation, but they are used for high-volume production. Descriptions of internally and externally heated salt bath furnaces, including illustrations, operating characteristics, advantages, disadvantages, and some of the precautions in use are given on pages 135 to 138 in the article "Liquid Carburizing", in Volume 2 of this Handbook. Figure 1 in the present article shows the typical construction of the four principal types of furnaces.

Externally heated furnaces are usually gas-fired or oil-fired and less frequently are heated by means of electrical resistance elements; with electrical resistance heating, pot failure may result in total destruction of the heating elements. The waste heat of flue gases from fuel-fired furnaces may be fed to an adjacent chamber and used to preheat workpieces.

Internally heated furnaces are energized with alternating current at 10 to 15 volts, supplied from a multiple-tap secondary transformer. The molten salt is an electrical conductor and heat is generated within the salt between the electrodes, from resistance to the passage of current. By closely spacing the electrodes, an electromagnetic stirring action of the salt is obtained that assists in maintaining temperature uniformity and a control of ±5 F.

Pot Materials. In salt bath brazing furnaces, the material used for construction of the pot depends on the type of salt that will be contained in it. The submerged-electrode furnace, which has a refractory brick lining, is not suitable for use with cyanide salts or water-soluble carburizing salts containing sodium carbonate or sodium cyanide, because of the rapid erosive effects of these chemicals on the lining of this type of furnace.

Because the salt pot of an externally heated furnace is ordinarily supported from a flange, as shown in Fig. 1(a) and (b), the pot size is limited by the strength of the material used. Externally heated pots for use with all types of brazing salt are made of metals ranging in composition from low-carbon steel to high-nickel-chromium alloys. A small furnace with a pot 10 in. in diameter and 12 in. deep would contain about 43 lb of salt; a fairly large furnace with a pot 24 in. in diameter and 30 in. deep would have a capacity of 700 lb of salt.

With internally heated furnaces, a ceramic (refractory) pot is usually preferred for neutral chloride salts and fluxing salts that consist of neutral chloride salts plus a fluxing agent such as borax or cryolite. Slight modifications can be made in the pot material when neutral salts and salts containing flux are used. When carburizing or cyaniding, in addition to brazing, is to be done, a steel or heat-resisting alloy pot must be used.

Salts

The types of salts used in dip brazing of carbon and low-alloy steels are: (*a*) neutral chloride salts, (*b*) neutral chloride salts plus a fluxing agent such as borax or cryolite, and (*c*) carburizing and cyaniding salts, which are also fluxing types of salts. Types and compositions of brazing salts and temperatures used for brazing of carbon and low-alloy steels with various filler metals are given in Table 1. (See also the safety precautions on page 660.)

Neutral salts, so called because normally they do not add or subtract anything from the surface of the steel being treated, protect the surface from attack by oxygen in the air. However, oxide on the workpiece cannot be reduced by the salt, and a flux must generally be provided.

The neutral salts are mildly oxidizing to steel when they are used at recommended austenitizing temperatures. The oxides produced by heating steel in molten salt are largely soluble; hence, the steel is scale-free after heating. However, the accumulation of oxide in the molten salt progressively makes the salt more strongly decarburizing, and for this reason baths must be rectified periodically, as discussed on page 225 in the article "Heat Treating of Tool Steel", in Volume 2 of this Handbook.

Flux that is applied to the surface of the assembly and dried before the assembly is immersed in the neutral salt will be quickly dissipated by dissolving in the salt or escaping from the surface of the bath as a volatilized salt, or gas. For this reason, there is generally no difficulty in removing flux from an assembly that has been brazed in a salt bath.

*For committee list, see page 593.

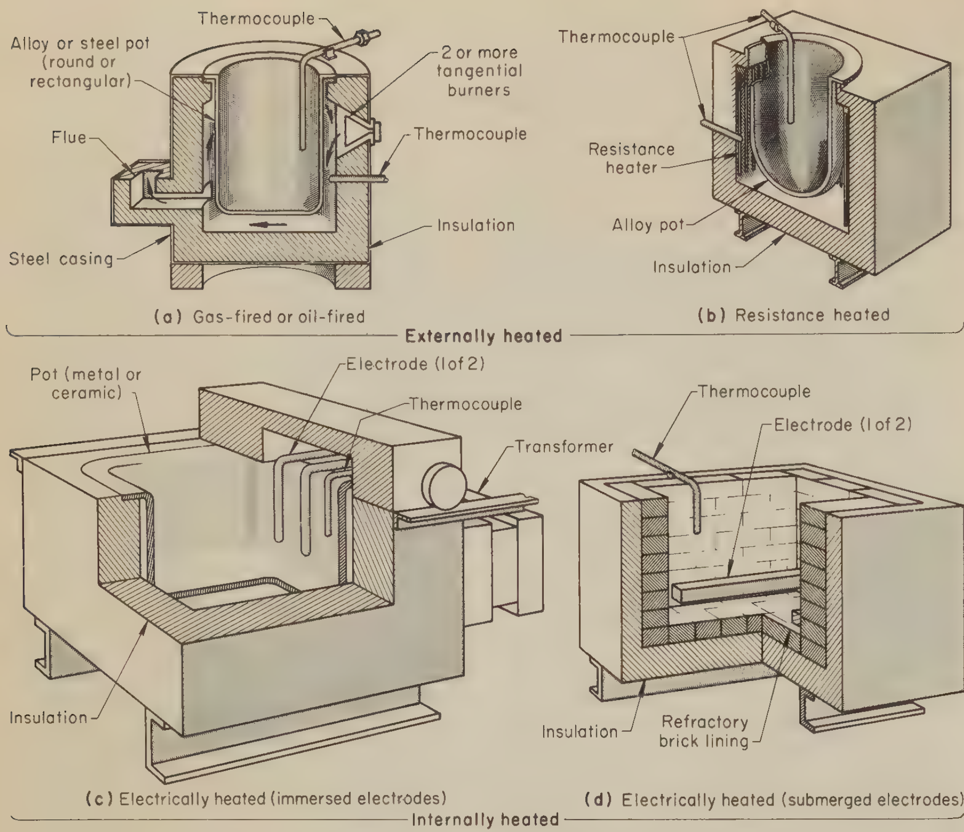


Fig. 1. Principal types of furnaces used for salt bath brazing

Fluxing agents such as borax and cryolite are added to neutral chloride salts to produce a fluxing environment in the bath. When these fluxing agents are used with silver alloy or copper-zinc filler metals, periodic flux additions are required, to maintain the fluxing potential of the bath. When the bath is operating at temperatures above 1200 F, the fluxing potential can be decreased rapidly by oxidation from contact with air or with the parts being brazed, and the fluxing agent must therefore be more frequently replenished. Sometimes a neutral chloride bath is used and the assembly prefluxed.

Carburizing and cyaniding salts provide their own fluxing action. In addition, they supply carbon and nitrogen to the surface of the steel assembly as it is being brazed. Although silver brazing alloys have been used successfully, RBCuZn-A filler metal is generally preferred. A case depth up to 0.012 in. can be obtained without adversely affecting the quality of a joint brazed with this copper-zinc filler metal. The following example describes the use of a carburizing salt bath for both carburizing and brazing. Cyaniding and carburizing in salt baths (without brazing) are discussed in detail in the articles "Cyaniding (Liquid Carbonitriding)", pages 129 to 132, and "Liquid Carburizing", pages 133 to 145, in Volume 2 of this Handbook. Also, see Table 1 on page 65 of Volume 2 for information on the use of salt baths.

Example 607. Combining Brazing and Carburizing in a Salt Bath (Fig. 2)

The 1010 steel assembly shown in Fig. 2 was part of a pair of adjustable self-clamping pliers. The jaw and a threaded bushing for the adjustment mechanism were brazed to the handle in a salt bath that, simultaneously with brazing, also carburized the bushing and handle.

The jaw was first separately carburized for 30 min in a water-soluble carburizing salt at 1675 F to obtain a deeper case than would be obtained in the time allowed for brazing. After being air cooled to room temperature, the jaw was washed and dried.

A hairpin-clip preform of RBCuZn-A copper-zinc filler metal and a tab on the carburized jaw were pressed in place in the handle, and the bushing with a preform ring of the same filler metal was pressed into the opposite end of the handle. Twenty-four assemblies were then loaded on a rack so that the jaws were held in place by the weight of the handles, as shown in Fig. 2. An interference fit held the bushing and handle together.

The rackload of assemblies was brazed and carburized by immersing for 20 min in a water-soluble carburizing salt bath at 1675 F, which also provided the fluxing action. The brazed assemblies were quenched directly in oil and then tempered until the jaw hardness was Rockwell C 48 to 51. The total case depth obtained on the jaw in the two carburizing operations was 0.010 to 0.012 in. A file-hard case about 0.004 to 0.005 in. deep was also developed on the threaded bushing and handle, which provided a hard wear-resistant surface to serve as a base for hard chromium plating.

Fluxes

An adequate fluxing environment is needed to assure good flow and penetration of the brazing alloy in salt bath brazing. When brazing is done in a neutral chloride salt bath, a flux is usually applied to the assemblies before brazing. Flux generally need not be applied to the assembly when using a cyanide bath or other fluxing bath.

Flux can be applied by brushing, dipping, or spraying the parts to be brazed before, during, or after assembly. After flux application, the assemblies must be preheated to dry them before immersion in the salt bath if there is any moisture present.

Typical fluxes employed for prefluxing carbon steels and low-alloy steels that are to be brazed in a salt bath are AWS types 3A and 3B.

Filler Metals

The brazing filler metals shown in column 1 of Table 1 are the most widely used for salt bath brazing of carbon and low-alloy steels. Although silver alloys BAg-13 and 13A (not shown in Table 1) can be used for brazing in a salt bath, they have been supplanted in most applications by copper-zinc alloys, which are less costly and have similar brazing temperature ranges. The rapid heating rate of steel in a salt bath minimizes dezincification of copper-zinc alloys, which facilitates the use of these alloys.

Although a temporary insulating cocoon of frozen salt forms instantly around a piece of cold metal when it is immersed in a salt bath, the temperature of a salt bath can, nevertheless, exceed the melting temperature range of the filler metal before the steel workpieces have reached a temperature high enough for proper wetting to take place. When this occurs, the molten filler metal will flow away from the joint with no brazing. It is therefore desirable to place the filler metal inside the joint in grooves, recesses, or drilled holes (Fig. 3 shows a recess type of arrangement). However, many assemblies of thin-section steel have been brazed successfully with the filler metal placed on the outside of the joint (see Fig. 5).

The brazing filler metal must be in contact with the joint. Filler metals in the form of wire, strip, powder, paste, and cladding are available. Special preform rings or other shapes can be obtained for specific joint requirements.

Joint Design

The filler metal providing the bond in brazed joints is drawn by capillary action between closely adjacent, substantially symmetrical surfaces. A diametral clearance of 0.001 to 0.003 in. is considered necessary for good flow and penetration of silver or copper-zinc filler metals in most joints. For copper brazing, joint clearance can range from a slight interference fit to a positive diametral clearance of about 0.002 in. When brazing dissimilar metals of differing coefficients of thermal expansion or dissimilar masses of the same metal, the design must take into account the differing rates of expansion so that the required joint clearance is obtained between the components at the brazing temperature.

For brazing, lap joints designed for shear loads are preferred to butt joints designed for tensile loads. Six designs for brazing using lap joints are compared with their counterparts commonly used for welding in Fig. 31 in the article on Furnace Brazing. For additional discussion of joint fit and design, the reader is referred to pages 607 to 610 in the same article.

Preparation for Brazing

Burrs can interfere with the capillary action and should be removed. The joint surfaces must be free of grease, oil, paint, oxide and scale that would prevent the filler metal from wetting the workpiece surfaces. (For cleaning methods, see page 602 in the article on Furnace Brazing, in this volume.)

Fluxing, as mentioned previously in this article, can be done before, during, or after assembly, as convenient, but the assembly must be warmed to eliminate any moisture before brazing.

Assembly. An assembly of self-jigging joints minimizes fixturing so that a hook, rod, basket, or rack may be all that is required to support the assembly during the brazing process. Methods of self-jigging are shown in Example 607 (gravity locating and press fitting), in Example 608 (thread joining) and in Example 610 (swaging). These and other methods are illustrated in Fig. 15 in the article on Furnace Brazing and discussed on pages 603 and 604 in that article.

Although the fixturing of workpieces that cannot be self-jigged creates such problems as distortion, difficulty in maintaining dimensional tolerances, and the need for heating an added mass of material, these difficulties can be overcome by careful fixture design, use of a fixture material of thermal expansion compatible with that of the work metal, and attention during brazing so that tolerances are maintained. The fixture material should also be compatible with the salt and flux used and have reasonably long life. The design of the fixture should facilitate draining after removal from the bath.

Preheating an assembly before brazing serves several purposes. If prefluxing is used, preheating dries the flux and vaporizes all moisture from the assembly and fixture. (Even a slight amount of moisture can cause spattering in contact with molten salt.)

Drying in an oven at 400 to 600 F before the assembly is immersed in the molten bath is recommended. However, warming of assemblies to about 200 F by laying them on top of the salt bath furnace is also done.

Preheating of assemblies will decrease the temperature drop of the salt bath and reduce brazing time, and can minimize the premature melting of externally placed filler metal. In joining an assembly consisting of both heavy and light sections, preheating reduces thermal gradients and subsequent distortion, as well as improving the wetting action on the heavier parts.

The preheating temperature must be lower than the solidus temperature of the filler metal and, when brazing carbon and low-alloy steels, is often several hundred degrees lower. In Example 609, the parts were preheated to about 1000 F prior to brazing with BAg-3 filler metal, which has a solidus temperature of 1170 F.

Brazing

General ranges of brazing temperature that are used with various salts are listed in the last column of Table 1 (this page); specific brazing ranges

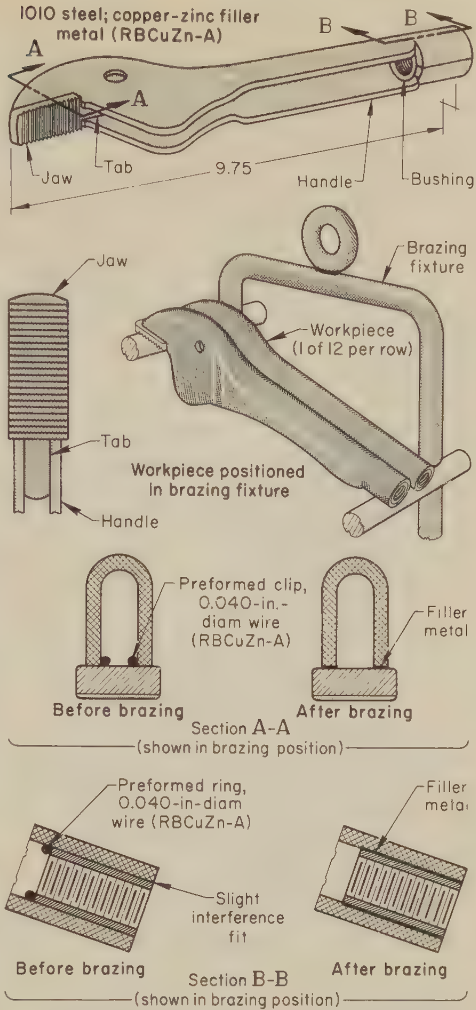


Fig. 2. Self-clamping-pliers part brazed in a salt bath (Example 607)

for the individual filler metals are given in Table 1 on page 627 in "Torch Brazing of Steel", and in Table 3 on page 599 in "Furnace Brazing of Steel".

The time in the molten salt bath differs from one job to another. For thin-section parts to be brazed only, the holding time may be as short as one minute. For assemblies that are to be case hardened as well as brazed, the holding time is the time required to produce the desired depth of case.

After the workpieces have been in the bath for the required time, they are carefully lifted from the salt bath. A uniform motion is necessary during removal from the bath; jerky movements can cause the liquid filler metal to be displaced from the joint.

Brazing and Heat Treating. It is possible to combine brazing with a heat treating operation such as neutral hardening or carburizing; the assembly can be air cooled to room temperature or quenched in a suitable liquid medium, as required.

If the assembly is to be quenched, it should cool in air until the brazing filler metal has fully solidified, before quenching. Otherwise, the filler metal will usually be blown out of the joint during quenching. This is more likely with water quenching than with oil quenching.

When molten salt baths are used for quenching, it is imperative that the salt used for the quenching bath be compatible with the salt used for the brazing and austenitizing bath. Neutral chloride salts are recommended for the brazing and austenitizing salt when a nitrate-nitrite salt is to be used as a quenching bath. The assembly must be air cooled until the filler metal solidifies before quenching in a nitrate-nitrite bath, as the molten salt will react with molten filler metal.

In the two examples that follow, salt baths were used to heat the assemblies for austenitizing and quenching. In the first example, the entire assembly was immersed and brazing was accomplished in the bath. In the second example, the assembly was only partially immersed, the joint being heated by conduction from the immersed portion. In addition, the joint clearances were considerably greater than those customarily used for brazing.

Example 608. Use of a Salt Bath To Braze and Harden in One Treatment (Fig. 3)

The breech-bolt assembly shown in Fig. 3 was brazed with a silver alloy filler metal and heated for hardening in one treatment.

Originally, a copper filler metal was used and brazing was done in a controlled-atmosphere furnace, but the bolt was completely annealed during furnace brazing and required subsequent hardening. After a preliminary investigation, it was found that this assembly could be brazed at the same time it was being heated for hardening in a salt bath.

The bolt assembly consisted of a bolt body of 1137 steel and a handle and guide lug of 1120 steel. The unit was assembled by placing a ring of BAg-1 filler metal in the bottom of the guide lug adjacent to the bolt body, and then screwing the handle

Table 1. Typical Salts Used for Salt Bath Brazing of Carbon and Low-Alloy Steels With Various Filler Metals

Filler metal(a)	Type of salt	Nominal composition, %	Brazing temperature range, F
BAg-1 through BAg-8, and BAg-18	Neutral	55 $BaCl_2$, 25 NaCl, 20 KCl	1150 to 1600
	Cyaniding-fluxing	20 to 30 Na_2CO_3, 20 to 30 KCl, 30 to 40 NaCN	1200 to 1600
	Neutral	50 NaCl, 50 KCl	1350 to 1600
RBCuZn-A	Neutral	80 $BaCl_2$, 20 NaCl	1675 to 1725
	Fluxing	79 $BaCl_2$, 20 NaCl, 1 borax	1675 to 1725
	Carburizing-fluxing (water soluble)	30 NaCl, 30 KCl, 20 carbonate, 15 to 20 NaCN, activator (proprietary)	1675 to 1725
RBCuZn-D	Neutral	90 $BaCl_2$, 10 NaCl	1900 to 1925
BCu-1 and 1a	Neutral	95 $BaCl_2$, 5 NaCl	2000 to 2100
	Neutral	100 $BaCl_2$	2000 to 2100

(a) For nominal compositions and brazing temperature ranges, see Table 1 on page 627 in "Torch Brazing of Steel" for silver alloys and copper-zinc alloys, and see Table 3 on page 599 in "Furnace Brazing of Steel" for copper filler metals. (b) Temperatures shown are those of the salt bath.

through the lug snugly into the threaded hole in the bolt body. This method of assembly held the filler metal in place so that, after brazing, the handle, lug, and bolt body would all be joined by brazing. The joints were coated with type 3A flux and dried by heating to 400 to 500 F.

The bolt assembly was then immersed in a salt bath for 7 min at 1550 F. The bath was a neutral chloride salt mixture containing 50% NaCl and 50% KCl. The bolt body was austenitized at the same time the filler metal penetrated the joints to be brazed. The assembly was immediately transferred to a nitrate-nitrite salt bath at 500 F for 7 min.

In this application, it was unnecessary to permit the filler metal to solidify before the quench; any exposed molten filler metal that was oxidized by the quench was removed in a later machining operation. The parts were then air cooled, tempered in a nitrate-nitrite bath at 820 F for 20 min, air cooled, and washed in hot water. The final hardness of the bolt body was Rockwell C 30 to 34, and the strength and quality of the brazed joint were completely satisfactory.

Example 609. Joining Carbide Tips to Tool Bits While Heating the Tool Bits for Hardening (Fig. 4)

Carbide-tipped rock bit drills, shown in Fig. 4, were joined using a silver brazing filler metal and heated for hardening in one operation in a salt bath. The bits ranged in diameter from 6 to 9 in. and weighed 100 to 300 lb. The shanks were made of air-hardening or oil-hardening tool steels.

Shanks and tips were vapor degreased and the surfaces to be joined were grit blasted and coated with flux. The carbide tips were inserted into the slots in the ends of the shanks with BAg-3 alloy shims placed under and on each side of each tip. Metal plates welded to the outer end of each slot, as shown in Fig. 4, kept flux and molten filler metal from escaping and kept the molten salt from entering when the assemblies were heated. (The plates were removed later by machining.)

The assembled bits were placed in a fixture with the carbide-tipped ends up, and were preheated to about 1000 F to dry the flux and assembly and to reduce the time required to reach austenitizing temperature in the salt bath. Each assembly was then partially immersed in the salt bath to a level at which the metal plates welded on the ends of the slots would safely prevent molten salt from entering the joint area. The assemblies were held in the bath for 20 to 30 min, depending on the size of the bit. This time period was needed to austenitize the shank and was not necessarily required for the joining operation. The tips were not submerged for three reasons:

1. To avoid thermal shock that might crack the carbide
2. To avoid washing away the flux
3. To keep the joints visible and accessible so that dry powdered flux and filler metal could be added to fill the joint.

The bath, a neutral chloride salt (50% NaCl, 50% KCl), was maintained at selected temperatures between 1600 and 1650 F, and held within ±5 F. The exposed ends of the assemblies, containing the joints being brazed, were heated only by conduction from the immersed portion. This lower heat input and the heat losses by radiation from the exposed metal served to keep the temperature in the joint area within the range (1270 to 1500 F) required to prevent overheating of the high-cadmium filler metal.

The assembly was air cooled or oil quenched, depending on the type of tool steel in the shank. During the cooling period, additional filler-metal rod and dry powdered flux were fed into the molten pool of BAg-3 alloy to fill the voids left by the approximately 20% shrinkage of the filler metal during solidification. After cooling, any salt remaining was washed from the bit, which then was tempered to the hardness specified for the shank.

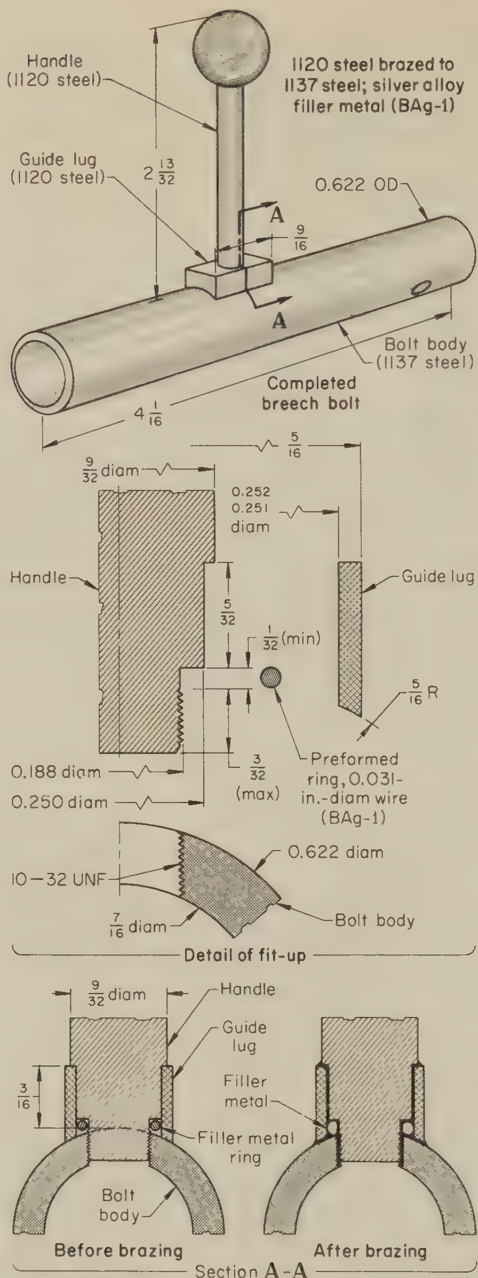


Fig. 3. Rifle breech-bolt assembly that was simultaneously heated for hardening and brazed in a salt bath (Example 608)

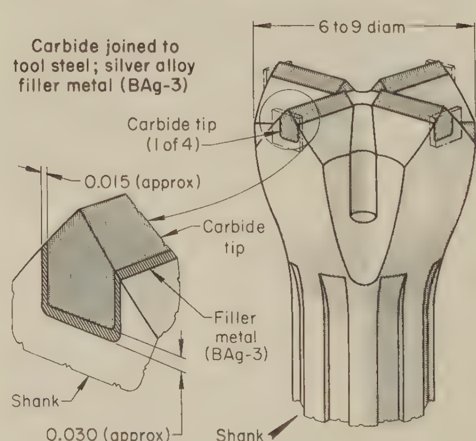


Fig. 4. Carbide-tipped rock bit that was joined using silver brazing alloy and simultaneously heated for hardening by partial immersion in a salt bath (Example 609)

The larger-than-normal clearances for filler metal (0.015 in. on each side and 0.030 in. under the carbide inserts) were found by field experience to provide a shock-impact cushion between the carbide and steel, which reduced the likelihood of premature failure.

Salt bath heating was selected because the rapid heating minimized oxidation and prevented breakdown of flux. In addition, several assemblies could be processed at one time.

Induction heating was rejected as a means of performing the operation because capacity would have been limited to one rock bit per station; high heat input would have demanded diffusion cycles to allow heat to be conducted from the surface to the interior of the heavy bits; temperature would have varied considerably in the carbide area, causing erratic melting and too many voids; overheating of carbide would have caused cracking; and subsequent over-all heating would have been necessary to harden the shank.

Torch brazing would have been unsatisfactory because: (*a*) uneven heating would have caused erratic melting of filler metal; (*b*) with localized heating, the whole bit would have required reheating to harden the shank; (*c*) flames from the various torches would have interfered with the operator's ability to monitor the joint and to face feed the filler metal after heating was completed; and (*d*) the torch flames would have caused excessive scale and spent flux, which would have had to be removed.

Use of cyanide salts in brazing baths allows carburizing, cyaniding or austenitizing to take place during brazing. However, the correct quenching medium must be chosen.

Safety Precaution. *The introduction of cyanide salts or other reducing agents into a nitrate-nitrite quenching bath will cause violent explosions.*

Because assemblies that are being brazed in salts containing cyanide must not be quenched in nitrate-nitrite salts because of the explosion hazard, and because the filler metal must solidify before quenching, the following procedure has been used:

A brazing filler metal such as RBCu-Zn-A is selected that will solidify above the transformation temperature range of the steel being brazed. The brazed assembly is transferred from the cyanide-containing bath into a neutral chloride salt bath rinse that is maintained below the solidus temperature of the filler metal but within the austenitizing range of the steel. The assembly is then transferred from the neutral chloride rinse to the nitrate-nitrite bath for the quenching operation. It is essential to control the amount of cyanide buildup in the neutral chloride rinse bath. When tests indicate more than 5% cyanide in the chloride rinse, part of the chloride salt should be discarded and the remainder diluted with the addition of new neutral chloride salt.

After quenching in the nitrate-nitrite bath, the assemblies are air cooled, washed, and then tempered, if tempering is required.

All fixtures must be thoroughly cleaned and dried after the quenching operation, to prevent transfer of nitrate-nitrite salt to cyanide baths or neutral chloride baths. Nitrate-nitrite salts will cause an explosion if mixed with cyanide, and a chloride bath contaminated with nitrate-nitrite salts will produce pitting and decarburization of steel parts immersed in it.

Further safety precautions applicable to the operation of nitrate-nitrite salt baths are presented on page 38 in Volume 2 of this Handbook.

Mechanized Brazing

The salt bath brazing process can be mechanized to increase production rates. Either semiautomatic or fully automatic handling mechanisms can be used, such as those described in the article on "Liquid Carburizing", page 139, in Volume 2 of this Handbook. A simple automatic arrangement is the "merry-go-round" described in Example 610, which follows. In this type of machine, the time at each station is the same. Different automatic arrangements have been used with conveyors to lift the workpieces in and out of the various furnaces and tanks in the line. One uses a bar and arm, from which the workpieces are suspended; another is the "jackrabbit" mechanism described in the referenced article. These and semiautomatic monorail transfer systems have the advantage that they can be set up with furnaces and tanks of different lengths so that the workpieces are held at each station for different lengths of time. A conveyorized production line was used in Example 611, which also follows.

Example 610. Partial Immersion of Assemblies During Brazing, To Preserve Work-Hardened Areas (Fig. 5)

Bicycle-fork assemblies made of 1010 steel were brazed in a salt bath using RBCuZn-A filler metal. Selective heating by partial immersion was necessary to retain, as nearly as possible, the strength developed in the side tubes by cold working. This was accomplished by suspending the fork so that only the stem tube, reinforcing plates and a portion (2¾ in.) of the side tubes were immersed in salt (see Fig. 5).

Originally the forks had been brazed in two gas-fired pots containing molten brass. The forks were preheated by laying them on top of the furnace and then were dipped in the molten brass, one fork at a time. A high degree of operator skill and rapid manipulation were required. Production rate was 75 forks per hour. Because loose fits (up to 1⁄32-in. clearance) were used, it was necessary to tack weld the assembly before brazing, to make it self-supporting. Rejects ran 2% and were not reworkable. Salt bath brazing was then tried.

A copper-zinc alloy, rather than copper, was selected as filler metal for salt bath brazing because copper-zinc permitted greater variation in joint clearance without sacrifice in joint strength, and the joint strength was about the same for both filler metals, although the brazing temperature with the copper-zinc alloy was lower (1700 F vs 2050 F). The lower brazing temperature required less heat and also minimized grain growth in the steel base metal.

The bicycle fork shown in Fig. 5 was assembled with the copper-zinc filler-metal rings in place and was made self-jigging by swaging the tubes into the reinforcing plates. To maintain alignment of the side tubes, a threaded rod with wing nuts was fastened in the slots at the hub end of the side tubes. This rod also provided the means of suspension. The joints were fluxed before brazing.

Because of the production requirements, brazing was done in a "merry-go-round" brazing machine, shown schematically in Fig 5. The machine consisted of six stations, with each station accommodating a fixture from which up to 14 fork assemblies were suspended. The fixtures were raised, lowered and indexed by arms that connected them to a central hydraulic cylinder. Time at each station was 3 min, with a 30-sec transfer time between stations.

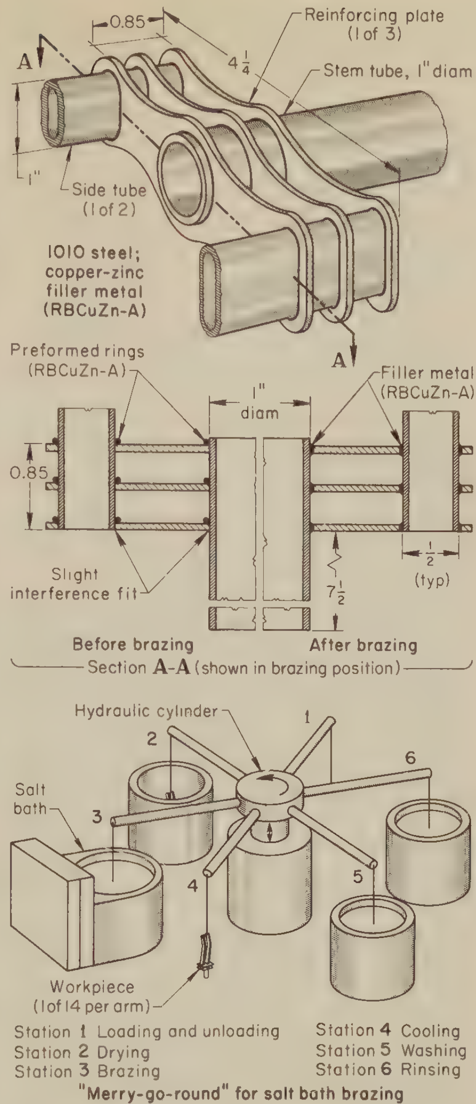


Fig. 5. Bicycle-fork assembly for which cost was reduced and production rate increased by changing from dip brazing one at a time in a bath of molten filler metal to mechanized brazing 14 at a time in a salt bath (Example 610)

Forks were hand-loaded and unloaded at the first station. Assemblies were dried at station 2 in a 5-kw electric drier. The salt bath brazing furnace at station 3 was an internally heated immersed-electrode furnace operated at 1700 F, using a neutral chloride salt composed of 80% $BaCl_2$ and 20% NaCl. Air cooling to solidify the filler metal followed at station 4. Stations 5 and 6 were a hot water wash and a hot water rinse. Unloading completed the cycle.

The new method increased production from 75 to 240 forks per hour, and resulted in a net saving of 7¢ per fork. Less than 1% of the forks showed defects, and these were salvaged by reworking.

Example 611. Use of Salt Bath Brazing for High Production (Fig. 6)

Steel tube-and-collar assemblies of various sizes from ¼ to 4 in. in outside diameter, one of which is shown in Fig. 6, were originally joined by induction brazing with silver alloy filler metal. Increased demands for the hydraulic systems in which these assemblies were used exceeded the capacity of the existing production facilities. As there were more than 20 sizes and some irregular shapes, the additional induction brazing equipment that would have been necessary to meet the production requirements was found to require an excessive equipment cost.

An attempt to braze the assemblies with copper filler metal in a controlled atmosphere furnace was only partially successful. The furnace was able to produce the needed quantity of work, but the much higher temperature required for copper brazing caused the tubes to warp enough so that they did not properly fit the mandrels that were used in a subsequent bending operation.

A production line for salt bath brazing was set up, consisting of an overhead conveyor that carried the assemblies through preheat, salt bath brazing and quenching operations. The shape of the production line was elliptical, to conserve floor space. The fixtures were made of type 304L stainless steel and were of a simple design suitable for holding tubes of a variety of sizes.

Production rate for salt bath brazing was 400 assemblies per hour, compared with 30 assemblies per hour using the original induction heating setup.

Before preheating and brazing, all parts were degreased (and pickled if necessary) and were placed on a wide-belt conveyor, which carried the parts through stations where all joints were flux coated, the parts assembled, and the assemblies hand loaded onto the brazing conveyor. A borax-base type 3A flux was applied by brushing.

The filler metal used was a silver alloy (50% Ag, 22% Cu, 20% Zn, 7% Cd, 1% Sn) having a solidus of 1125 F and a liquidus of 1145 F. Assembly consisted of placing a preformed ring of 0.062-in.-diam filler-metal wire in the collar and inserting the tube, as shown in Fig. 6. The filler-metal ring was confined by a bevel on the end of the tube so that it would be retained during the brazing operation. A diametral clearance of 0.001 to 0.003 in. was maintained between the collar and the tube. The tubes were gravity located in the collars (a self-jigging joint) and the fixture was limited to holding the collar and giving lateral support to the tube.

Gas burners were used to preheat the assemblies to dry them. The preheat temperature was about 500 F.

The assemblies were partially immersed (the joint area only) in the salt bath and held until they reached bath temperature.

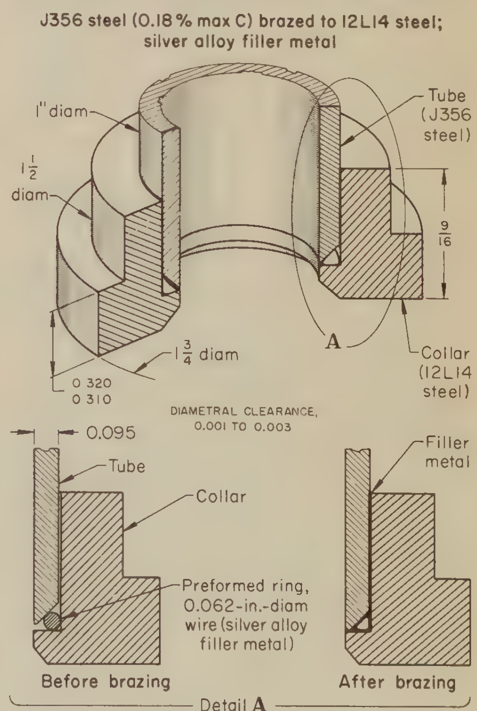


Fig. 6. Tube-and-collar assembly that was salt bath brazed on a mechanized production line (Example 611)

The salt bath furnace was a submerged-electrode type, 13½ in. wide by 48 in. long by 25 in. deep. The pot was lined with firebrick. A neutral chloride type of salt bath composed of sodium and potassium chlorides was used. The bath was maintained at 1600 F (to minimize dragout) by on-off switching, with an over-temperature alarm. The bath was rectified, when needed, by bubbling methyl chloride gas through it. Fumes from the bath were exhausted for pollution control.

After brazing, the assemblies were quenched in cold water and hand unloaded from the conveyor. The quench provided enough cleaning, since the assemblies were to be pickled and plated after bending. This same brazing procedure was used for low-carbon, high-carbon and alloy steels.

Safety Precautions

Cautions and references for the safe use of nitrate-nitrite salt baths and oil quench tanks, and for the need for all parts to be free of moisture before immersion in a salt bath, have been included earlier in this article. The same protective equipment for personnel suggested on page 145 in Volume 2 of this Handbook applies to all salt bath operations and includes long heat-resisting gloves, an asbestos apron, and a face shield or safety glasses, or both.

Salt bath brazing may produce dusts, fumes and gases hazardous to health. Therefore, adequate exhaust systems and ventilation are necessary. For example, cadmium is contained in some silver alloy filler metals. Cadmium oxide fumes are toxic, and inhalation of these fumes can be fatal. Other metals, salts and materials present various degrees of hazard.

The fluorides in fluxes pose a dual problem: It is necessary not only to provide adequate ventilation to carry away fumes, but also to avoid skin contact with these fluxes and to provide means to make it unnecessary for anyone to place his hands in the flux.

Table 2. Threshold Limit Values (TLV) for Substances Encountered in Salt Bath Brazing
(See text for discussion of TLV)

Substance	TLV, mg per cubic meter(a)
Barium (soluble compounds)	0.5
Cadmium oxide fume	0.1
Copper dusts and mists	1.0
Cyanide (as CN) — Skin(b)	5.0
Fluoride (as F)	2.5
Hydrogen cyanide — Skin(b)	11.0
Hydrogen fluoride	2.0
Silver metal and soluble compounds	0.01
Zinc oxide fume	5.0

Source of data and text summary: "Threshold Limit Values of Airborne Contaminants and Intended Changes Adopted by ACGIH for 1970", American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio 45202.

(a) Approximate milligrams of particulate per cubic meter of air. (b) "Skin" following a substance indicates that the substance can penetrate the skin to cause systemic effects.

Brazing personnel should thoroughly wash their hands before making any body contacts or handling food.

Two brazing salts listed in Table 1 contain cyanide. If taken internally, cyanides are fatally poisonous; if allowed to come in contact with scratches or wounds, they are highly toxic. Fatally poisonous fumes are evolved when cyanides are brought into contact with acids. To avoid possible toxic effects, it is recommended that an exhaust system be provided to remove the fumes from salt baths. Precautions in the use of cyanide salts and the disposal of cyanide wastes are discussed further on page 145 in Volume 2 of this Handbook.

Threshold limit values (TLV) of airborne concentrations of substances commonly encountered in salt bath brazing are given in Table 2. A summary of some of the limitations of these values follows, but the reader is directed to the reference in Table 2 for complete information. Threshold limit values represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect. They are time-weighted concentrations for a 7-or-8-hr workday and a 40-hr week. They should be used as guides in the control of health hazards, but not as fine dividing lines between safe and dangerous concentrations.

These values are intended for use in the field of industrial hygiene and should be interpreted and applied only by persons trained in that field. They are *not* intended for use, or for modification for use: (*a*) as a relative index of toxicity or hazard, (*b*) in the evaluation or control of community air pollution or air-pollution nuisances, (*c*) in estimating the toxic potential of continuous, uninterrupted exposures, or (*d*) as proof or disproof of an existing disease or physical condition.

References. In addition to the reference in Table 2 and the article on cyanide baths in Volume 2, the reader is referred to the following sources of detailed information on safe practices, cautions and hazards in brazing:

"Safety in Welding and Cutting", American National Standard Z49.1

"Specification for Brazing Filler Metal", AWS A5.8, American Welding Society

Safe Practices in Welding and Cutting, "Welding Handbook", 6th edition, Section 1, Chapter 9, American Welding Society.

Other Examples of Salt Bath Brazing

Examples of salt bath brazing presented elsewhere in this volume describe joining of: malleable iron to 1010 steel (Example 614); type 304 stainless steel to copper alloy 230 (Example 630); aluminum alloy 6061 (Example 632); and copper alloy 220 to cast bronze (Example 661).

Brazing of Cast Irons

BRAZING gray, ductile and malleable cast irons differs from the brazing of steel in two principal respects: (*a*) special precleaning methods are necessary to remove graphite from the surface of the iron, and (*b*) the brazing temperature is kept as low as feasible, in order to avoid reduction in the hardness and strength of the iron.

The processes used for brazing cast irons are the same as those used for brazing steel — furnace, torch, induction and dip brazing. As with other metals, selection of the brazing process depends largely on the size and shape of the assembly, the quantity of assemblies to be brazed, and the equipment available. For information on brazing equipment and general procedures, see the articles on pages 593 to 660 in this volume.

Filler Metal and Flux. Because most cast irons are brazed at relatively low temperatures, the filler metals used are almost exclusively silver brazing alloys. Compositions and other information concerning the more common silver alloy filler metals are listed on page 610 in the article on Furnace Brazing in this volume. Of these silver alloys, BAg-1 is most often used for brazing of cast iron, mainly because it has the lowest brazing-temperature range. A fluoride-type flux such as AWS type 3A is usually used with BAg-1 filler metal.

Brazeability

Relatively high silicon content and sand inclusions on as-cast surfaces have some adverse effects on the brazeability of cast iron, but these effects are less significant than the adverse effect of graphite, which is present in all gray, ductile and malleable cast irons. Graphite has essentially the same effect on machined joint surfaces as on as-cast surfaces. Although gray, ductile and malleable irons all have lower brazeability than carbon or low-alloy steels, the three types of iron are not equal in brazeability.

Malleable iron is generally considered the most brazeable of the three common types of cast iron, largely because the total carbon content is somewhat lower (seldom over 2.70%), and because the graphite occurs in the form of approximately round nodules and thus is easier to remove or cover up (as by abrasive blasting). Also, malleable iron is lower in silicon than the other types of cast iron, which makes it better suited for brazing.

Ductile iron can have a composition nearly the same as gray iron, but the graphite particles are spheroidal rather than flake-shape. The spheroidal shape is more favorable for brazing. Shot or grit blasting is effective in rolling metal over graphite particles that are exposed at the surface.

Gray iron, which is characterized by large flakes of graphite, is the type of cast iron most difficult to braze. Until the development of electrolytic salt bath cleaning, brazing of gray iron was considered impractical.

Applicability

Brazing is sometimes used to repair defective or damaged castings, although braze welding is more often used for this purpose (see the article on Oxyacetylene Braze Welding of Steel and Cast Irons, which begins on page 579 in this volume).

Most brazing of cast iron is done to join assemblies at lower cost than is possible by another process, or to fabricate parts that are difficult to produce as one-piece castings (see Example 612). In some applications, two or more cast iron components are brazed together; in other applications, one or more components of a brazed assembly are made of another metal — most often, of steel (see Examples 613 and 614). Copper alloys and cast iron can also be joined by brazing with silver alloy filler metal.

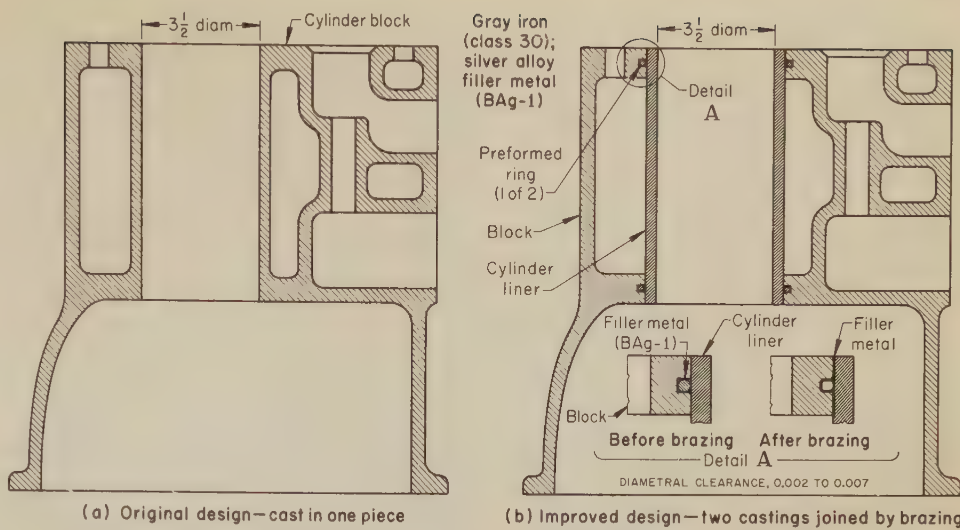


Fig. 1. Cross sections of gray iron cylinder blocks made originally as a single casting and subsequently by joining two castings by furnace brazing (Example 612)

Preparation of Castings for Brazing

Preferred joint designs for brazing cast iron are generally the same as for steel. Best results are obtained by the use of diametral clearances in the range of 0.002 to 0.005 in. Diametral clearances up to 0.010 in. may be used, but this much clearance will result in lower joint strength and added filler-metal cost.

Methods of Surface Preparation. A number of methods have been tried for preparing cast iron surfaces for brazing; most of them have been only partly successful.

Abrasive blasting with steel shot or grit has proved reasonably successful for preparing the surfaces of ductile and malleable iron castings, but is seldom suitable for preparing surfaces of gray iron castings. Other methods that have been used with only moderate success include a variety of pickling and other chemical treatments, searing with an oxidizing flame, and heating to 1600 to 1650 F in a strongly decarburizing atmosphere.

Electrolytic treatment in a molten salt bath, alternately reducing and oxidizing, has been the most successful method for surface preparation and is applicable to all graphitic cast irons.

Before any procedure for cleaning is adopted, it is advisable to make tests by cleaning samples of the iron that will be used for the castings to be brazed and then fluxing them and applying filler metal (preferably on a smooth, flat surface). The samples are then heated to the pre-established brazing temperature, cooled, and examined visually. If the samples show indication that the filler metal has not uniformly wetted the test piece, the surface is not sufficiently clean.

Electrolytic Salt Bath Cleaning. The cleaning method that has proved most effective as a means of preparing cast iron surfaces for brazing is basically the same as the sodium hydroxide type of descaling described in the article on Salt Bath Descaling, page 357, Volume 2 of this Handbook, except that the bath described in that article is a two-tank system. The salt used for cleaning is sodium hydroxide plus additives.

For cleaning cast iron, the salt bath is usually operated at 850 to 900 F. Direct current is passed through the bath during the process, and by changing polarity, the action of the molten bath can be changed from oxidizing to reducing, or vice versa.

Castings are immersed in the bath, suspended from bus bars or fixtures, which are insulated from the tank that contains the molten salt. Common practice is first to make the castings negative and the tank positive; with this polarity, the action of the bath is reducing. During this portion of the cycle, particles of sand are removed and oxides are reduced. The direction of the current is then reversed and oxidation begins. During this portion of the cycle, graphite is removed from the surface of the castings. The current is again reversed and the cycle is completed under reducing conditions. Castings then are immersed in water, to finish the cleaning and to rinse away the salt, and are dried.

A typical processing cycle is described in greater detail in Example 613 (column 3, this page) and in the table accompanying Fig. 2 (next page).

Preheating. To minimize brazing time and to dry the flux when brazing in a furnace or a salt bath, it may be advisable to preheat assemblies containing one or more cast iron components. As cast irons have moderate to high thermal expansion coefficients, coupled with relatively low thermal conductivities, it may be advisable also to preheat the entire assembly to a temperature between 400 and 800 F before torch or induction brazing, to reduce temperature differences.

Production Applications

The three examples presented in this section deal with the brazing of gray iron to gray iron, gray iron to steel, and malleable iron to steel.

Foundry problems involved in producing complex castings can sometimes be overcome by producing two or more simpler castings and brazing them together. Not only is it difficult to make molds for castings with complex internal passages, but removing the cores and burned-in sand from the castings may be even more difficult. The example that follows describes a typical use of joining two gray iron castings by brazing to replace a complex casting.

Example 612. Brazing Two Castings for an Engine Cylinder Block (Fig. 1)

The gray iron cylinder block for which a sectional view is shown in Fig. 1(a) was originally machined from a single casting. Not only were the cores for the internal passages difficult to mold, but removing the core sand from the casting was an additional problem.

Both difficulties were overcome by changing from the one-piece design to two castings brazed together as shown in Fig. 1(b). Mating surfaces of the block and cylinder liner were finish machined so that diametral clearance was 0.002 to 0.007 in. Two grooves were machined in the block, as shown in Fig. 1(b), to receive the preformed filler-metal wires.

Both of the cast components were then cleaned electrolytically in a molten salt bath. [A procedure similar to that described in Example 613 was employed.]

The two castings were then assembled, with the preformed rings of filler-metal wire (BAg-1) and flux (type 3A) trapped in the grooves, and brazed in a furnace at 1325 F under a protective atmosphere.

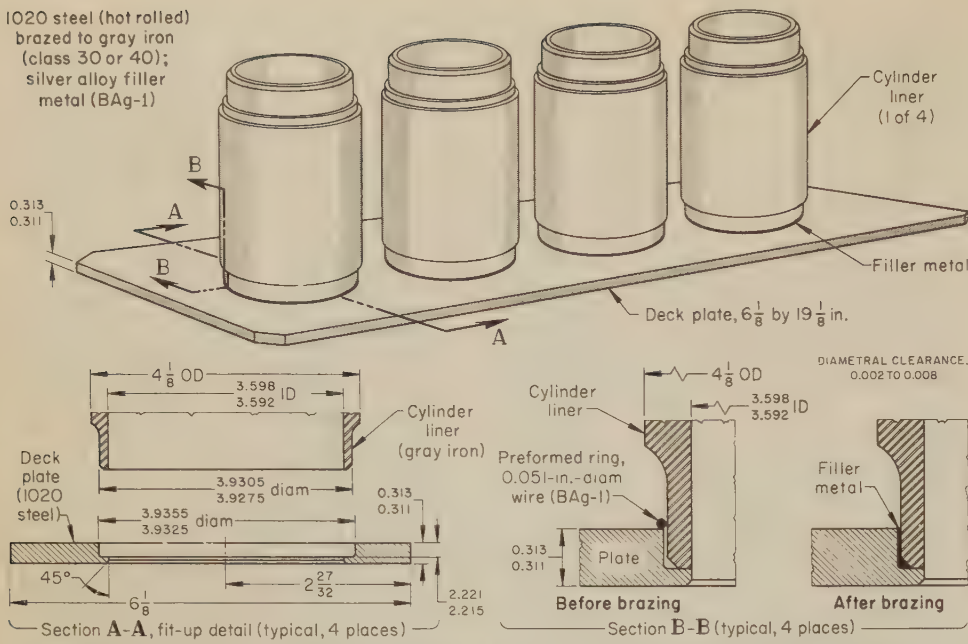
Brazing cast iron to steel may be done to attain a specific set of properties, to simplify the casting process, or to reduce cost. In the example that follows, four gray iron castings were brazed to a wrought steel plate.

Example 613. Brazing Four Gray Iron Cylinder Liners to a Steel Deck Plate (Fig. 2)

The brazed assembly shown in Fig. 2, consisting of four centrifugally cast cylinder liners of class 30 or 40 gray iron and a deck plate of 1020 steel, served as a component of a gasoline engine.

All five parts of the assembly shown in Fig. 2 were machined to the sizes shown, which permitted a diametral clearance of 0.002 to 0.008 in. between each gray iron liner and the steel plate.

In preparation for brazing, the steel plate was cleaned by degreasing in trichlorethylene. The gray iron liners were cleaned electrolytically in a bath of molten salt at 860 F for a total time of 35 min, after which they were immersed first in cold water and then in water at 160 F. (Details of the cleaning equipment and of the processing procedure used are given in the table that accompanies Fig. 2.)



Electrolytic Salt Bath Prebraze Cleaning	
Tank size	4 by 3½ by 4 ft high (usable volume)
Tank capacity	13,000 lb of molten salt
Salt composition	Principally sodium hydroxide
Current	1800-amp dc (reversible polarity)
Bath temperature	860 F
Reduction-oxidation cycle:	
Reduction (workpiece negative), agitator on	5 min
Oxidation (workpiece positive), agitator off	20 min
Reduction (workpiece negative), agitator on	10 min
Total time in bath	35 min
Salt removal:	
Dip hot castings	Cold water
Dip cold castings	Water at 160 F

Conditions for Furnace Brazing	
Furnace	Roller hearth, multiple zone
Electrical heating power	330 kw
Furnace zone length:	
Vestibule	4 ft, 2 in.
Heating zone	22 ft, 6 in.
Slow-cooling zone	10 ft
First water-cooled zone	6 ft, 10 in.
Second water-cooled zone	5 ft, 4 in.
Third water-cooled zone	6 ft, 11 in.
Atmosphere	Exothermic, 6.5-to-1 air-to-gas ratio
Furnace temperature	1300 F
Filler metal	BAg-1
Flux	Type 3A
Brazing time, door-to-door	144 minutes
Production rate	62½ assemblies per hour

Fig. 2. Gray iron cylinder liners furnace brazed to a steel deck plate for a gasoline engine, after being cleaned in an electrolytic salt bath (Example 613)

Immediately after prebraze cleaning, the following fluxing and assembly procedure was used.

1 The deck plate was placed on a carbon block that was supported by the furnace tray.
2 A liner was placed in a fixture that held it at a 45° angle above a pot containing type 3A flux in paste form.
3 A degreased ring of BAg-1 filler metal was placed around the liner ¼ in. from the end to be joined to the plate.
4 Flux was applied to the end of the liner by lowering it into the flux pot as far as the filler-metal ring, and rotating the liner while holding it at a 45° angle. This procedure served to place a uniform coat of flux on the end of the liner for a distance of about ¼ in. from the end.
5 The liner was then removed from the fluxing fixture and placed in one of the holes in the plate (Fig. 2).
6 The filler-metal ring was then pushed down into position against the plate (see section B-B in Fig. 2).
7 A 4½-lb weight was then hung in the liner bore to ensure that the liner would retain its position during brazing.

The above procedure was followed for each liner. The assembly was then brazed by the following procedure.

1 The assembly, on its carbon block and tray, was pushed into the vestibule of a 330-kw multiple-zone roller-hearth furnace.
2 The assembly then entered the heating zone under an exothermic atmosphere at 1300 F, where the brazing was accomplished.
3 From the heating zone, the assembly moved into the slow-cooling zone, then through three consecutive water-cooled zones and was finally removed at a temperature of 300 F maximum.

Total time in the heating zone for each assembly was 60½ min. Soaking at brazing temperature was approximately 15 min. Total time in the furnace for each assembly was 144 min (door-to-door). By following the procedure outlined here, the assemblies were brazed at an average rate of 62½ per hour.

After brazing, each assembly was cleaned ultrasonically in a solution of 10 oz of rust stripper per gallon, rinsed in cold water, and dipped in a solution of 2 oz of alkaline rust preventive per gallon.

Quality of the brazed joints was checked visually by the furnace operator, and verified by fluorescent-penetrant inspection.

The application described in Example 613 is one of numerous similar applications performed in various plants. Details of processing procedure vary considerably among plants, although surface preparation by the use of electrolytic salt bath cleaning is general.

Retention of Strength. Cast irons that contain pearlite or free carbide graphitize and decrease in strength at elevated temperatures. Because graphitization is a function of both time and temperature, some experimentation is usually necessary to develop a brazing cycle that will produce acceptable joints without excessive graphitization and decrease in strength.

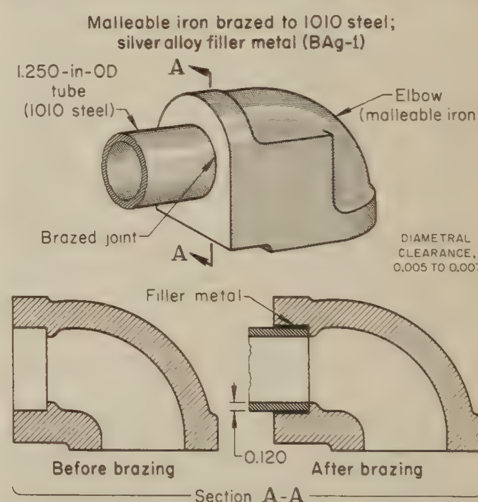
In Example 613, the assemblies were heated for an hour at 1300 F maximum, with no significant decrease in strength. In a similar application, in another plant, the assemblies were heated to about 1450 F without significant decrease in strength. However, in the latter application, heating was by induction instead of in a furnace, and the heating time was very much shorter than would have been required in a furnace.

In some plants using furnace brazing, the furnace is operated at a considerably higher temperature than is desired for brazing (sometimes as high as 1600 F), but using time cycles so short that the assemblies never reach furnace temperature.

For applications in which little or no decrease in the strength of the cast iron can be tolerated, it is mandatory to use a filler metal with as low a flow-temperature range as possible, thus permitting a low brazing temperature, and to keep the time at brazing temperature to the minimum.

The temperature required for wetting the base metal and for flow of filler metal having a melting range of 1145 to 1195 F may vary from about 1275 to 1550 F, depending on the complexity of the joint design, especially the distance the filler metal must flow. Simple joints with short flow distances can be brazed at lower temperatures than more complex joints.

Dip Brazing in a Molten Salt Bath. One of the more common applications for brazing of cast iron is the joining of steel tubing to headers, special fittings and stanchions. Various mechanical assemblies are brazed to cast iron because different metal properties are needed in different parts of the assembly or, more often, because the fitting portion of such an assembly can be



Conditions for Salt Bath Brazing	
Furnace	Pit-type salt bath(a)
Salt	Sodium chloride and potassium chloride(b)
Fixtures	Type 304L stainless steel
Prebraze cleaning:	
Steel tube	Degrease
Cast fitting	Electrolytic salt bath clean(c)
Filler metal	BAg-1
Flux	Type 3A
Brazing bath temperature	1600 F(d)
Time in salt bath	Varied with load(d)
Postbraze cleaning	Water quench

(a) Brick lined, 48 in. long, 13½ in. wide, and 25 in. deep. Heated by three-phase, 60-cycle, 460-volt, 110-kw, submerged electrodes; with on-and-off temperature control and over-temperature alarm. (b) Rectified with methyl chloride to maintain neutrality. (c) See conditions given in table with Fig. 2. (d) Temperature of parts probably did not exceed 1425 F.

Fig. 3. Malleable-iron-to-steel fitting assembly dip brazed in molten salt (Example 614)

made most economically from cast iron. Such assemblies can be satisfactorily brazed by torch, induction, atmosphere furnace, or salt bath processes. Selection of process depends mainly on the quantity to be brazed and the equipment available.

In the example that follows, dip brazing in molten salt was selected for joining a cast fitting of malleable iron to steel tubing, because it was possible to achieve a higher production rate than by other available processes. The particular type and size of fitting assembly discussed in this example is one of many that are joined by brazing. In some larger sizes, the casting is made of gray or ductile iron instead of malleable iron.

Example 614. High-Production Dip Brazing of Malleable Iron Fittings to Steel Tubing (Fig. 3)

Malleable iron elbow castings, like the one shown in Fig. 3, were used to connect hydraulic pressure lines of 1010 steel tubing to standard ports.

Diametral clearance of 0.005 to 0.007 in. between the tube and the casting was maintained by boring the casting holes; this clearance ensured good capillary flow of the silver alloy filler metal. Free graphite on the machined surfaces of the castings was removed by electrolytic salt bath cleaning. [The electrolytic cleaning was similar to that described in Example 613.] The filler metal was BAg-1, and the flux was type 3A.

Three methods of heating for brazing were available: with gas burners, by induction, and in a salt bath. Heating with gas burners was too slow to be economical. Induction heating was satisfactory, but the production rate obtained with the available induction equipment was lower than with the available salt bath equipment. Therefore, the salt bath was selected.

The salt bath system included a semiautomatic conveyor (manually loaded and unloaded) that carried the assemblies through the bath, which was maintained at 1600 F, and through a subsequent water quench, which removed the salt. The time in the salt bath was such that the assembly did not reach bath temperature.

Fixtures were of type 304L stainless steel and were designed so that assemblies of various sizes could be accommodated. Additional conditions for salt bath brazing are given in the table that accompanies Fig. 3.

In the foregoing example, the salt bath was operated at 1600 F. This high temperature will severely reduce the strength of many cast irons. If this decrease in strength cannot be tolerated, either of two methods can be used for brazing in a salt bath: (*a*) employ a salt that can be used without excessive dragout at a temperature lower than 1600 F, or (*b*) develop a time cycle short enough that the temperature of the casting never exceeds about 1425 F.

In Example 614, the assemblies containing the malleable iron castings were water quenched to remove the brazing salt — a practice that is common with steel assemblies. However, to avoid warpage and cracking, brazed assemblies containing gray and ductile iron castings should never be water quenched from the brazing temperature. Instead, the assemblies should be cooled slowly to about 300 F and then immersed in water to remove the salt.

Brazing of Stainless Steel

*By the ASM Committee on Welding and Brazing of Stainless Steel**

ALL OF THE standard wrought stainless steels can be brazed satisfactorily, although their brazeability — in common with their weldability — varies with composition. In general, the more weldable stainless steels are also the more brazeable. Neverthless, the quality of brazed joints can often be improved by judicious selection of brazing process, brazing temperature, filler-metal composition, and protective atmosphere or activating flux, provided that such selection is compatible with performance in service.

Applicability. Brazing of stainless steels is most widely used for joining them to dissimilar metals, including stainless steels of dissimilar composition, carbon steels, low-alloy steels, copper alloys, and titanium. In fact, a principal advantage of brazing is that it can join a stainless steel to a variety of dissimilar metals to which it cannot be satisfactorily welded. Nine of the 17 examples in this article deal with the brazing of dissimilar-metal combinations (see Table 1). In addition, brazing makes it possible to select from a wide variety of brazing filler-metal compositions to achieve compatibility, strength, corrosion resistance and other desirable properties when dissimilar metals are to be joined.

When the most appropriate heating techniques are employed, brazing provides a method for obtaining strong, corrosion-resistant, leaktight joints in small or thin-wall components with a minimum of buckling or warpage. Brazing can produce joints in delicate assemblies that would be difficult or impossible to obtain with conventional welding processes. Brazing also lends itself to the mass production of small and medium-size assemblies on various types of continuous equipment. Finally, brazing makes possible the production of joints in inaccessible locations by the preplacement of filler metal and subsequent heating of the workpiece; often, such joints cannot be made by other joining processes.

Brazeability. As a class, stainless steels are more difficult to braze than are carbon and low-alloy steels. The difficulty is associated with the high chromium content of stainless steels, which accounts for the presence of chromium oxide films on the surface of all stainless steels. These oxides, which are refractory and strongly adherent, prevent wetting of the base metal by the molten filler metal.

The formation of chromium oxide is accelerated when stainless steels are heated in air. Therefore, although the oxide may have been removed from the surface by chemical cleaning at room temperature, a new oxide layer will form rapidly when the steel is heated in air to the brazing temperature and will seriously interfere with wetting. The adverse effect of oxides on wetting can be alleviated in any of four ways:

1 The steel can be chemically cleaned of surface oxide at room temperature, and shortly thereafter be heated to the brazing temperature in a chemically inert gaseous atmosphere, such as argon. This approach is seldom used, because the wetting action in inert gas is marginal.
2 The steel, after less intensive cleaning, can be heated directly to the brazing temperature in a strongly reducing atmosphere, such as dry hydrogen, which will chemically reduce the oxide and thereby promote wetting action.
3 The area at the joint can be coated with a chemically active flux that, during heating to the brazing temperature, will dissolve the oxide.
4 Heating and brazing can be done in a vacuum (after cleaning), thus preventing exposure to oxygen or water vapor and enabling effective wetting

Inclusions and Surface Contaminants. Base-metal inclusions and surface contaminants are even more deleterious in the brazing of stainless steel than they are in the brazing of carbon steel. Base-metal inclusions such as oxides, sulfides and nitrides interfere with the flow of filler metal. Flow is also impeded by surface contaminants, which may include lubricants such as oil, graphite, molybdenum disulfide, and lead, which are applied during machining, forming and grinding.

Some of the filler-metal powders (in paste form) used with stainless steel contain organic binders; acrylics and other plastics are often used for this purpose. Although some binders form a soot residue, this residue usually does not interfere with filler-metal flow.

The brazing characteristics of stainless steel can also be seriously impaired by unsuitable fixturing materials, such as graphite, or by a protective atmosphere with a nitriding potential. Carbon in graphite fixtures will unite with hydrogen to form methane (CH_4), which will carburize stainless steel and impair its corrosion resistance. Dissociated ammonia, unless sufficiently dry and completely (100%) dissociated, will nitride stainless steel. Both carburizing and nitriding will interfere with brazing quality.

Brazing Processes. Stainless steels can be brazed by all conventional brazing processes, including furnace, torch, induction, resistance and salt bath

*For committee list, see page 245. More than half the examples presented in this article were contributed by members of other Metals Handbook welding and brazing committees.

Table 1. Summary of Brazing Conditions Employed in Examples in This Article

Example	Name of assembly	Base metals brazed	Filler metal	Brazing temperature, F	Brazing atmosphere	Time at brazing temp, minutes
Furnace Brazing						
616	Retainer	Type 347	BAg-13	1700 ± 10	Hydrogen	5
617	Heat exchanger	Type 347	BAu-4	1860	Hydrogen	7 to 10
618	Switch cover	Types 303, 305 and PH 15-7 Mo	BAg-19	1750 ± 15	Hydrogen	10
619	Heat exchanger	Type 347	BNi-3	1950 ± 10	Hydrogen	5
620	Shaft	Type 410	BCu-1 and BCu-2	2050 ± 10	Hydrogen	8
621	Impeller	Type 410	BNi-3	2000 ± 10	Hydrogen	5
622	Impeller	Type 403 and 12.5% Cr steel(a)	BCu-1	2050-2075	Hydrogen	25
623	Pressure-gage diaphragm	Type 304, 17-7 PH, and Cu alloy 145	BAg-19	1800	Dissoc. ammonia	5
624	Tableware handle	Type 430 or type 302	(b)	2000	Dissoc. ammonia	4½ to 6
625	Gear-reduction box	Type 347 and titanium	BAg-19	1650 ± 10	Argon	1 max
626	Gas-valve bobbin	Types 446 and 303, and Cu alloys	BAg-3	1370 to 1450	Air	1 max
Torch Brazing						
615	Tube and sleeve	Type 304L	BAg-18	...	Air	...
627	Tube	Type 304 and pure nickel	BAg-1a	1175	Air	...
Induction Brazing						
628	Solenoid tube	Type 321 and type 416	BAg-1	1200	Air	⅙
629	Temperature sensor	Types 302, 303 and 304	BAg-7	...	Argon (backing)	⅔
Dip Brazing						
630	Wave guide	Type 304 and Cu alloy 230	BAg-3	1350	Molten salt	1½
Electron Beam Brazing						
631	Capillary tube in tube	Type 304	BCu-1a	2050	Vacuum	½

(a) Type 304 locating pins were also brazed to both metals. (b) 20 Ag, 40 Cu, 9 Ni, 26 Zn, 5 Cd.

brazing. Furnace brazing is most widely used, because for most applications brazing in a prepared atmosphere or in a vacuum is required. The extensive use of furnace brazing is demonstrated by the fact that, out of the seventeen examples of brazing applications presented in this article (and summarized in Table 1), eleven are concerned with furnace brazing.

Filler Metals

Most stainless steels can be brazed with any one of several different filler metals, including silver alloys, nickel alloys, copper, and gold alloys. Copper alloy filler metals that contain phosphorus (the BCuP group) are never used for brazing steels, because of the brittle phosphides and intermetallics formed at the joint interface. In most applications, filler metals are selected for mechanical properties, corrosion resistance, and compatibility, rather than for brazeability.

Table 2 lists compositions, solidus and liquidus temperatures, and applicable brazing-temperature ranges of the filler metals most often used for the brazing of stainless steels. Table 1 lists the filler metals used in the 17 examples presented in this article.

Silver alloys (the BAg group) are the most widely used filler metals for brazing stainless steel. Alloy BAg-3, which contains 3% nickel, is probably the most widely used of the silver alloys, although several other silver alloys are also used and have proved successful (see Tables 1 and 2).

Silver brazed joints cannot be used for high-temperature service. Recommended maximum service temperature is 400 F. Recommended allowances on joint fit for silver brazing are relatively loose — generally, 0.002-in. to 0.004-in. diametral clearance.

Of the silver alloy filler metals shown in Table 2, all except BAg-19, and possibly BAg-13, are used at brazing temperatures that fall within the effective range of sensitizing temperatures (1000 to 1600 F) for austenitic stainless steels. It is in the sensitizing-temperature range that carbide precipitation occurs, resulting in impairment of the corrosion resistance of the base metal. Carbide precipitation, however, depends on time as well as on temperature, and exposure to the sensitizing-temperature range for only a few minutes is unlikely to result in a significant amount of precipitate. Nevertheless, the lower melting temperatures of the silver alloys prohibit re-solution treatment of the base metal after brazing, and if corrosion resistance in service is sufficiently critical, either an extra-low-carbon type or a columbium-tantalum-stabilized type should be selected instead of a nonstabilized austenitic steel.

Also, it should be noted that all of the silver alloy filler metals contain appreciable amounts of copper and zinc, singly or in combination. Overheating or heating for an excessive period of time may result in extensive penetration of grain boundaries by copper and zinc, thereby embrittling the brazed joint. Cadmium, which is added to some silver alloy filler metals to lower the melting temperature, will also penetrate grain boundaries. Cadmium-containing fumes are extremely toxic, and operators must take every precaution to avoid inhaling them. Cadmium fumes also will attack furnace parts and fixtures.

Zinc-containing and cadmium-containing silver alloy filler metals are not suitable for brazing components that

Table 2. Nominal Compositions, Solidus and Liquidus Temperatures, and Brazing-Temperature Ranges of Filler Metals Commonly Used in Brazing of Stainless Steels (AWS A5.8-69)

AWS classification	Composition, % Ag	Cu	Zn	Cd	Ni	Cr	Si	Sn	B	Fe	Other	Temperature, F Solidus	Liquidus	Brazing
Silver Alloy Filler Metals														
BAg-1	45	15	16	24	...	...	...	...	...	...	...	1125	1145	1145 to 1400
BAg-1a	50	15.5	16.5	18	...	...	...	...	...	...	...	1160	1175	1175 to 1400
BAg-3	50	15.5	15.5	16	3	...	...	...	...	...	...	1170	1270	1270 to 1500
BAg-7	56	22	17	...	...	...	...	5	...	...	...	1145	1205	1205 to 1400
BAg-13	54	Rem	5	...	1	...	...	...	...	...	...	1325	1575	1575 to 1775
BAg-18	60	Rem	...	...	...	...	...	10	...	...	...	1115	1325	1325 to 1550
BAg-19	92.5	Rem	...	...	...	...	...	...	...	...	0.2 Li	1435	1635	1610 to 1800
Nickel Alloy Filler Metals														
BNi-1	...	...	...	...	Rem	14	4	...	3.5	4.5	0.75 C	1790	1900	1950 to 2200
BNi-3	...	...	...	...	Rem	...	4.5	...	3.1	1.5 max	...	1800	1900	1850 to 2150
BNi-7	...	...	...	...	Rem	13	...	...	...	...	10 P	1630	1630	1700 to 1900
Copper Filler Metals														
BCu-1	...	99.90 min	...	...	...	...	...	...	...	...	...	1980	1980	2000 to 2100
BCu-2	...	86.5 min	...	...	...	...	...	...	...	...	...	1980	1980	2000 to 2100
Gold Alloy Filler Metal														
BAu-4	...	...	...	...	Rem	...	...	...	...	...	81.5 Au	1740	1740	1740 to 1840

will be exposed to high vacuum in service. Selection of a suitable silver alloy filler metal for service in vacuum at pressures below 10^{-5} torr is considered in the following example.

Example 615. Selection of Filler Metal for a Type 304L Brazement Used in High Vacuum (Fig. 1)

The sleeve-and-tube assembly shown in Fig. 1 is typical of brazements used in vacuum systems. The tubes and the sleeve were of type 304L austenitic stainless steel.

Virtually all of the silver alloy filler metals are suitable for brazements used in vacuum chambers and pumps at pressures that are as low as 10^{-5} torr. However, for high-vacuum work (pressures of less than 10^{-6} torr), the filler metal must not contain cadmium or zinc. These metals will vaporize, interfering with the production of the vacuum and possibly contaminating the vacuum chamber and pumps. Consequently, filler metal BAg-18 (60% Ag, 10% Sn, rem Cu), which has proved satisfactory for brazing of assemblies used in high-vacuum applications, was used, with type 3B flux.

Brazing was done with a manually manipulated oxyacetylene torch, using a strongly reducing flame. The assembly shown in Fig. 1 could have been brazed in a furnace or by induction, but production was small and did not justify the investment for such equipment.

Ferritic and martensitic stainless steels that contain little or no nickel are susceptible to interface corrosion in plain water or in moist atmospheres when brazed with nickel-free silver alloy filler metals, using a liquid or paste flux. Filler metal containing nickel will help to prevent interface corrosion. However, for complete protection, special brazing alloys containing nickel and tin should be used and brazing should be done in a protective atmosphere without flux.

Nickel alloys (the BNi group) usually rank next to the silver alloys in frequency of use as brazing filler metals for stainless steels (see Table 1). Nickel alloy filler metals provide joints that have excellent corrosion resistance and high-temperature strength. However, they alloy with stainless steel and form phases that have two undesirable characteristics: (*a*) they are considerably less ductile than either the base metal or the filler metal, even at elevated temperatures, and thus are a potential source of rupture; and (*b*) the alloys formed with stainless steel are higher-melting alloys that are likely to freeze and block further flow into the joint during brazing. This does not usually cause difficulty in a shallow joint, for which zero clearance is generally recommended. However, to achieve flow in deep joints, diametral clearances of as much as 0.004 to 0.008 in. are necessary. Knurling of male members sometimes helps in centering loosely fitting components. With such large clearances, joints brazed with nickel alloy filler metals do not develop their greatest strength. With zero clearance, the braze metal contains less base metal and therefore is stronger.

Because of the relatively high brazing temperatures required for the nickel alloy filler metals (see Table 2), their use is generally restricted to furnace brazing in a reducing atmosphere, although there are occasional exceptions (see Fig. 16 and related text).

Type 304L; silver alloy filler metal (BAg-18)

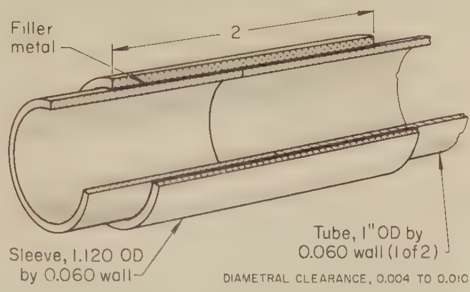


Fig. 1. Assembly that was torch brazed with a silver alloy filler metal containing no zinc or cadmium, because of use of the brazement in a high-vacuum system (Example 615)

Copper filler metals (the BCu group) melt at about 1980 F and flow freely at 2050 F. Copper is not recommended for exposure to certain corrosive substances, such as the sulfur in jet fuel and in sulfur-bearing atmospheres. When a copper filler metal is used, recommended diametral allowances on joint fit range from 0.004-in. clearance to 0.002-in. interference.

The high brazing temperature and the need for a protective atmosphere generally restrict the use of copper filler metal to furnace brazing.

Gold alloys (the BAu group) are sometimes used for brazing stainless steel. The high brazing temperatures required and the high cost of the gold alloys restrict the use of these filler metals to specialized applications (see Example 617). When a gold alloy is used, alloying with the stainless steel base metal is minimized and, as a result, joints exhibit good ductility.

Fluxes

For furnace brazing in strongly reducing or inert atmospheres, flux usually is not required. However, in some furnace brazing applications a flux is necessary (see Example 624). A flux is always required for torch brazing and is usually required for induction and resistance brazing, unless atmospheric protection is provided.

Either of two AWS types of flux (3A and 3B) is suitable for all stainless steel brazing applications where a flux is needed. Both types are available in powder, paste and liquid forms.

Type 3A flux contains boric acid, borates, fluorides, fluoborates and a wetting agent. Its effective temperature range is 1050 to 1600 F. It is suitable for use with silver alloy filler metals.

Type 3B flux contains the same ingredients as type 3A, but not in the same proportions, and has a higher effective temperature range (1350 to 2100 F). This type of flux is often selected for use with silver alloy filler metals if the brazing temperature is above 1350 F, and is well suited for use with copper (BCu), nickel alloy (BNi), and gold alloy (BAu) filler metals.

Furnace Atmospheres

Almost all furnace brazing of stainless steel is done in a protective gas or in vacuum. One exception is the application described in Example 626, in which air was the furnace atmosphere. In this application, a flux was used and the time at brazing temperature was short, which helped to prevent excessive oxidation.

The protective atmospheres most often used in furnace brazing of stainless steel are dry hydrogen and dissociated ammonia; both are effective in reducing oxides, protecting the base metal and promoting the flow of filler metal. The low-cost exothermic atmospheres that are widely used in furnace brazing of low-carbon steel are not suitable for stainless steel. An inert gas, such as argon, or vacuum may be used to satisfy special requirements and to provide protection in applications for which hydrogen or hydrogen-bearing gases are unsatisfactory.

Selection of furnace atmosphere depends on the degree of protection that must be given to the base metal or metals, the flow characteristics of the filler metal, the brazing temperature, and cost. Special requirements that arise from the brazing of dissimilar metals are often a major factor in atmosphere selection. Availability of equipment may also be of importance. Ten of the eleven examples of furnace brazing that are presented in this article involve the use of protective atmospheres, including dry hydrogen, dissociated ammonia, and argon.

Furnace Brazing in Dry Hydrogen

A dry hydrogen atmosphere is preferred for many applications of brazing stainless steel, and was used in seven of the 11 examples in this article that deal with furnace brazing. Hydrogen, the most strongly reducing of protective atmospheres, reduces chromium oxide and provides for excellent wetting by some filler metals without the need for flux. The principal disadvantages of hydrogen are its high cost, the difficulty in getting it sufficiently dry, the need for special furnace equipment, and the danger involved in storing and handling hydrogen.

Examples of Practice. The first six of the seven examples that follow describe applications in which a specific type of stainless steel was joined to the same type or to another stainless steel. (The sixth of these examples describes an application in which changing from gas tungsten-arc welding to furnace brazing decreased cost and increased production rate.) The seventh example describes brazing of stainless steels to a low-carbon low-alloy steel.

Example 616. Selection of BAg-13 Silver Alloy Filler Metal for Brazing at 1700 F (Fig. 2)

The type 347 stainless steel retainer assembly shown in Fig. 2 was furnace brazed in dry hydrogen, using BAg-13 silver alloy filler metal. This filler metal was selected in preference to lower-melting silver alloys because the upper limit of the brazing-temperature range of BAg-13 (1575 to 1775 F) permitted brazing at 1700 F. At furnace temperatures above 1600 F, dry hydrogen is strongly reducing, and the use of a brazing flux is not required for satisfactory wetting action. Thus, by judicious selection of filler metal and furnace atmosphere, the extra costs of applying a flux, and of removing flux residue after brazing, were avoided.

The components were vapor degreased, assembled with outside diameters concentric, and (to make them self-jigging) were spot welded at four locations, 90° apart (see Fig. 2). A ring of 0.040-in.-diam filler-metal wire was preplaced at the joint, and assemblies were loaded two-across on the mesh belt of a conveyor-type furnace. The heating chamber of the furnace was elevated from the entrance and discharge level to conserve the lighter-than-air hydrogen. Production rate and additional processing details are given in the table with Fig. 2.

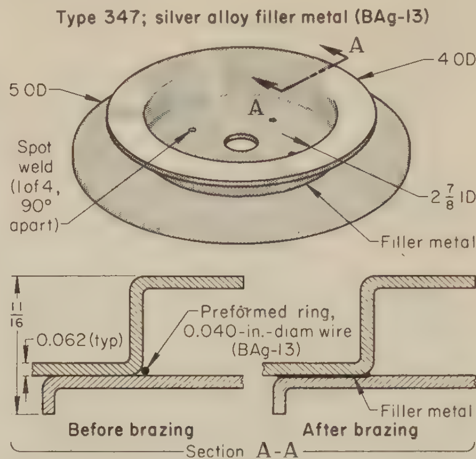
Quality standards for brazed assemblies, which were checked by 100% visual inspection, required that the joint exhibit full braze penetration (360° fillets on both sides of the joint) and be pressure-tight.

Example 617. Use of a Gold Alloy Filler Metal for Brazing of 5104 Joints in an Aerospace Heat Exchanger (Fig. 3)

In the fabrication of a high-reliability heat exchanger for manned space flights, 2552 type 347 stainless steel fins 0.004 in. thick were brazed to 0.025-in.-thick type 347 stainless steel side panels, as shown in Fig. 3. The 5104 fin-to-panel joints had to be strong and corrosion resistant.

Silver alloy and copper brazing filler metals could not be used because of incompatibility with sulfur-bearing rocket fuel. The BNi series of nickel alloys had the necessary compatibility, but made brittle joints that were unreliable under tension peel stress. Therefore, gold alloy filler metals were considered. The necessary brazing characteristics for the fin-to-panel joints were found in BAu-4 (81.5% gold, remainder nickel). The strength and toughness of the brazed joints made with this alloy justified its high cost.

The fins and side panels were cleaned by vapor degreasing. The side panels were pickled, rinsed in clean water and dried. The filler metal was coated on the panels in the form of a powder suspended in an organic binder. Multiple lap joints were made between the flat-crown-hairpin ends of the fins and the flat side panels. The assembly was placed in a fixture (see Fig. 3), and the entire assembly and fixture were placed in the retort of a bell-type furnace and sealed. The sealed retort was purged with a volume of hydrogen equivalent to five times that of the retort. The retort was then heated to the brazing temperature of 1860 F and held for 7 to 10 min. Joint gap at brazing temperature was 0.000 to 0.010 in. Then the retort was purged with argon while being cooled to 300 F, and was not opened until after purging and cooling.



Furnace Brazing in Dry Hydrogen

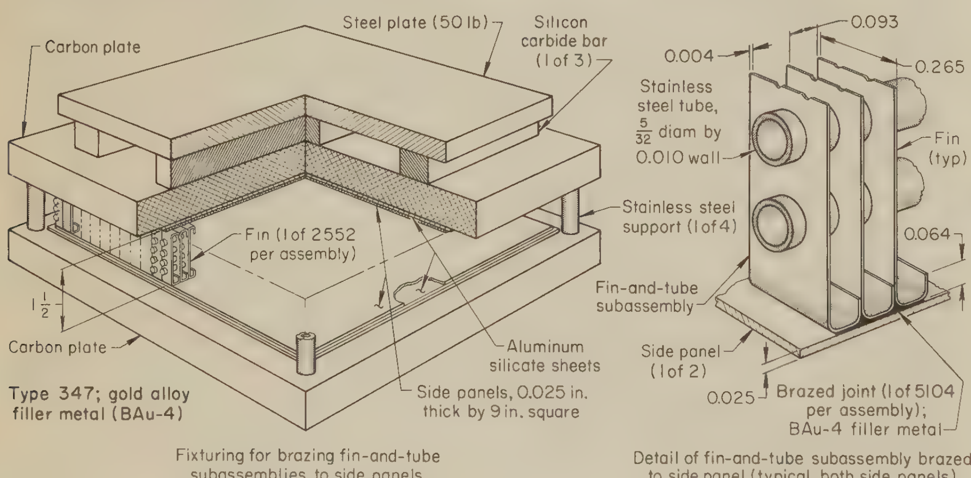
Furnace	Continuous conveyor(a)
Fixtures	None
Furnace temperature	1800 ± 10 F
Brazing temperature	1700 ± 10 F
Hydrogen dew points	—100 F (incoming); —70 F (exhaust)
Hydrogen flow rate	400 cu ft per hour
Filler metal	BAg-13, 0.040-in.-diam wire(b)
Joint position during brazing	Horizontal
Conveyor travel speed	30 ft per hour
Time at brazing temperature	5 min(c)
Production rate	120 assemblies per hour

(a) Electrically heated (60 kw), constructed with heating chamber (6 in. high, 12 in. wide, 36 in. long) higher than entrance and discharge ends. (b) Preformed full rings. (c) Cooled in hydrogen atmosphere to room temperature.

Fig. 2. Retainer assembly that was furnace brazed at 1700 F, using BAg-13 filler metal (Example 616)

The joints brazed by the above procedure were the final brazed joints in the assembly. In a prior brazing operation, tubes had been joined to the fins (see Fig. 3) by brazing at 1970 F using a higher-melting gold alloy filler metal composed of 70% gold, 22% nickel and 8% palladium.

Completed assemblies were visually inspected and pressure tested at pressures that far exceeded the pressures to be encountered in service. Typical service pressures were 270 psi on the outside of the tubes and 1710 psi on the inside. Acceptance pressure tests were at 540 psi on the outside of the tubes and 2275 psi on the inside. Selected brazed assemblies were tested to bursting. These samples were required to withstand at least three times the service pressures before bursting. The assemblies brazed with gold alloy filler metals passed all tests and had three times the bursting strength of assemblies brazed with nickel alloys. Additional brazing conditions are given in the table with Fig. 3.



Furnace Brazing in Dry Hydrogen

Furnace	Bell(a)
Fixtures	(See illustration)
Brazing temperature	1860 F
Hydrogen dew point (max)	—80 F(b)
Purging	5 volume changes in retort
Filler metal	BAu-4(c)
Number of assemblies per load	One

Processing Time per Assembly

Clean components	45 min
Preplace filler metal	1¼ hr
Assemble components in fixture	4 hr
Brazing (time at temperature)	7 to 10 min
Total time in furnace(d)	4 hr
Inspect	1 hr
Pressure test	40 hr

(a) Electrically heated, with 36-in.-diam retort with water-cooled rubber seals. (b) Hydrogen was purchased as cylinder hydrogen, then passed through an electrolytic drier. (c) 200-mesh powder suspended in an organic binder. (d) Including cooling to 300 F in retort, which was purged with argon before being opened.

Fig. 3. Heat-exchanger assembly, in brazing fixture, and detail of joints between 2552 fins and two side panels, which were brazed with gold alloy filler metal to obtain required strength (Example 617)

Example 618. Combination Brazing and Solution Heat Treatment of an Assembly of Three Types of Stainless Steel (Fig. 4)

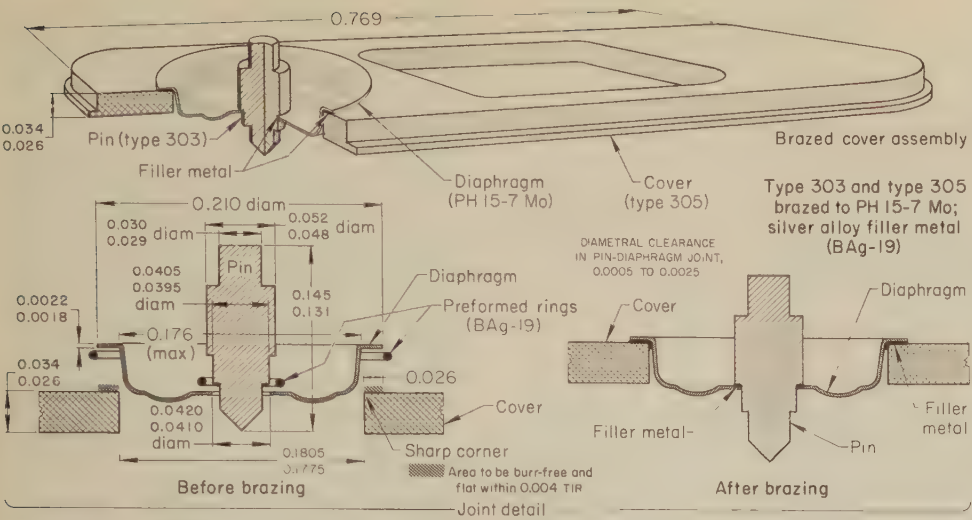
Three different stainless steels were selected to make the cover for a hermetically sealed switch. The switching action had to be transmitted through the cover without breaking the seal. This was accomplished by providing a diaphragm through which a shouldered pin was inserted, as shown in Fig. 4. The switch was actuated by depressing the pin, which, in turn, deflected the diaphragm. The pin, of type 303, the diaphragm, of PH 15-7 Mo, and the cover, of type 305, were assembled as shown in Fig. 4 and furnace silver brazed in dry hydrogen.

Silver alloy filler metal BAg-19 was chosen, because it flowed at a temperature that coincided with the solution heat treating temperature for the PH 15-7 Mo diaphragm (1750 F). A holding fixture was needed to keep the PH 15-7 Mo diaphragm in position during the brazing cycle; to avoid carburizing the diaphragm, the material selected for the fixture was stainless steel, rather than graphite. The furnace was a batch-type tube furnace with a 5-in.-diam high-heat zone 18 in. long. Moisture content of the hydrogen atmosphere was carefully controlled, because with too dry an atmosphere, the lithium-containing filler metal flowed too freely and did not seal the joints.

After being cleaned, the components were assembled with two preformed rings of BAg-19 wire; tweezers were used to avoid contamination of the cleaned surfaces. Each assembly was held in a stainless steel fixture, which in turn was placed on a stainless steel furnace sled. The sled was pushed into the high-heat zone of the furnace and held at 1750 F for 10 min, pulled into an intermediate cooling zone at 1000 F and held for 5 min, and finally pulled to the water-cooled zone, where it cooled to room temperature. Brazing of the two joints and solution treating of the PH 15-7 Mo diaphragm were accomplished simultaneously at the brazing temperature (1750 F). To complete the heat treating process, the assembly was cooled to —100 F, held for 8 hr, and then aged at 950 F for 1 hr.

A 1-in.-square piece of PH 15-7 Mo was processed with each batch of cover assemblies, and was used as a hardness-test specimen to verify that the diaphragms had been correctly heat treated. Brazed assemblies were inspected by the brazing operator. It was required that the joints be fully sealed and have no voids, and that the pins be perpendicular within 4°. Perpendicularity was measured on a comparator. Randomly selected samples were given a push-out test, in which joints had to withstand a push of 14 lb. All assemblies were given 100% visual inspection at a magnification of 13 diameters.

Additional brazing conditions are given in the table with Fig. 4.



Conditions for Furnace Brazing in Dry Hydrogen

Furnace	Batch-type tube(a)	Time at brazing temperature	10 min
Fixture material	Stainless steel(b)	Time in first cooling zone (1000 F)	5 min
Brazing temperature	1750 ± 15 F	Time in final cooling zone(d)	5 min
Filler metal	BAg-19 wire(c)	Production in 8 hr	1000 assemblies

(a) Three-zone furnace, with a high-heat zone 5 in. in diameter by 18 in. long. (b) Fixture located and held components of assembly together, and was placed on a stainless steel sled for transport through the furnace. (c) Preformed rings. (d) Water-cooled zone, in which assembly was cooled to room temperature. Then, to complete heat treatment of the PH 15-7 Mo diaphragm, assembly was cooled to −100 F and held for 8 hr, then aged at 950 F for 1 hr.

Fig. 4. Three-steel switch-cover assembly for which time at brazing temperature was also part of solution heat treatment of the PH 15-7 Mo diaphragm (Example 618)

Example 619. Simultaneous Brazing of 370 Joints in a Heat-Exchanger Assembly (Fig. 5)

An air-to-air heat-exchanger assembly, shown in Fig. 5, consisted of 185 thin-wall (0.008-in.) tubes and two 1/16-in.-thick headers. All components were made of type 347 stainless steel. The tubes were assembled with the headers by flaring the tube ends to lock them in place and provide metal-to-metal contact for brazing filler metal. All 370 joints were brazed during a single pass through a continuous conveyor-type electric furnace.

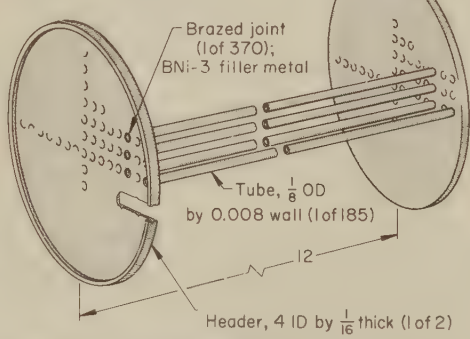
Although a nickel alloy filler metal was preferred for this high-temperature application, because of the resistance to heat and corrosion that nickel alloys provide, selection among the nickel alloys presented a problem. Higher-melting, boron-containing nickel filler metals, such as BNi-1 and BNi-3, alloy with the base metal and therefore are likely to erode thin materials. Fortunately, the extent of erosion can be modified by control of the brazing temperature and time, and the amount of filler metal.

Although there are nickel filler-metal alloys that contain silicon in place of boron, these alloys generally require much higher brazing temperatures, which can result in grain coarsening in the base metal. Therefore, after numerous tests, BNi-3 filler metal was selected on the basis of brazing temperature and excellent fluidity, and the problem of applying the correct amount of filler metal to avoid erosion was solved by preparing a slurry from an accurately controlled mixture of filler-metal powder, acrylic-resin binder, and xylene thinner.

Before the filler metal was applied, the heat-exchanger assembly was cleaned ultrasonically in acetone, and was carefully weighed to determine the proportionate weight of filler metal required. One-half the total amount of filler metal was then applied to one end of the assembly by spraying. The assembly was then reweighed, and the remainder of the filler metal was applied to the opposite end. At all stages of processing, the assembly was handled by operators wearing clean lint-free white cotton gloves.

The assembly was placed on a holding fixture made of stainless steel sheet, to which a stop-off compound had been applied to prevent the assembly from brazing to the fixture if the brazing filler metal flowed excessively. Assemblies were placed 12 in. apart on the conveyor belt as they traveled through the furnace at 30 ft per hour under protection of dry hydrogen. Additional furnace details and brazing conditions are given in the table with Fig. 5.

Type 347; nickel alloy filler metal (BNi-3)



Furnace Brazing in Dry Hydrogen

Furnace	Continuous conveyor(a)
Fixture material	Type 347 stainless steel(b)
Furnace temperature	2050 ± 10 F
Brazing temperature	1950 ± 10 F
Hydrogen dew points	−100 F (incoming); −70 F (exhaust)
Hydrogen flow rate	600 cu ft per hour
Filler metal	BNi-3 powder(c)
Conveyor travel speed	30 ft per hour
Time at brazing temperature	5 min
Cooling	In hydrogen atmosphere
Production rate	15 assemblies per hour

(a) Electrically heated (60 kw), constructed with heating chamber (6 in. high, 12 in. wide, 36 in. long) higher than entrance and discharge ends. (b) Holding fixture fabricated from 1/8-in.-thick sheet. (c) Mixed to a slurry with acrylic resin and xylene thinner; powder-to-vehicle ratio, 70 to 30.

Fig. 5. Heat-exchanger assembly with 370 tube-to-header joints that were brazed in one pass through a furnace (Example 619)

After brazing, both sides of each joint were subjected to 100% visual inspection for the presence of fillets; assemblies were pressure tested in accordance with customer requirements.

Because of the thin-wall (0.008-in.) tubing, brazing this assembly provided more consistent results than could have been achieved by gas tungsten-arc welding. In addition, the cost of welding 370 joints would have been many times the cost of furnace brazing.

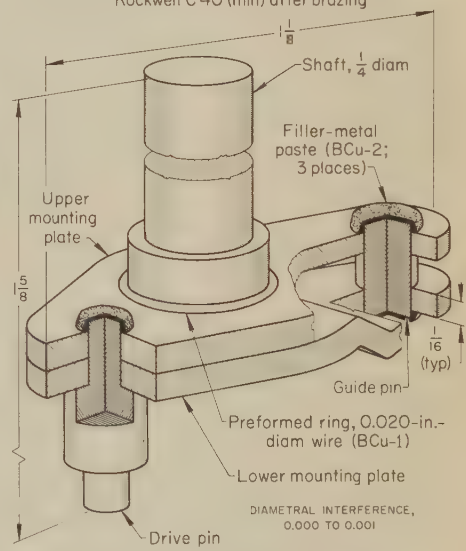
Examples 620 and 621. Combining Brazing and Hardening of Assemblies Made of Type 410 Stainless Steel

Example 620 — Shaft Assembly (Fig. 6). The shaft assembly shown in Fig. 6 consisted of three bar machine products (a shaft, a drive pin and a guide pin) and two stampings (upper and lower mounting plates), all made from type 410 stainless steel, that were furnace brazed together with four joints. By brazing with copper filler metal at 2050 F, it was possible to austenitize and harden the assembly to the required minimum hardness of Rockwell C 40 during the brazing and cooling operations, thereby avoiding a separate hardening operation after brazing.

Because the joints were all relatively short, an interference fit of 0.000 to 0.001 in. was satisfactory. (Normally, with longer joints in stainless steel, a clearance fit between mating parts is required.) Automatic staking of components was used to make the assembly self-fixturing.

As shown in Fig. 6, a full ring of 0.020-in.-diam BCu-1 copper wire was preplaced

Type 410; copper filler metals (BCu-1 wire, BCu-2 paste); Rockwell C 40 (min) after brazing



Furnace Brazing in Dry Hydrogen

Furnace	Continuous conveyor(a)
Fixtures	None(b)
Furnace temperature	2150 ± 10 F
Brazing temperature	2050 ± 10 F
Hydrogen dew points	−100 F (incoming); −70 F (exhaust)
Hydrogen flow rate	400 cu ft per hour
Filler metal	BCu-1 wire, BCu-2 paste(c)
Conveyor travel speed	20 ft per hour
Time at brazing temperature	8 min(d)
Cooling	In hydrogen atmosphere
Production rate	800 assemblies per hour

(a) Electrically heated (60 kw), constructed with heating chamber (6 in. high, 12 in. wide, 36 in. long) higher than entrance and discharge ends. (b) Components were staked, for self-fixturing. Assemblies, supported by ceramic spacers to keep shaft end up, were brazed on trays. (c) 0.020-in.-diam wire in a preformed ring; paste was applied at one end of drive pin, both ends of guide pin. (d) Assemblies were in high-heat zone for about 10 min.

Fig. 6. Four-joint shaft assembly that was simultaneously furnace brazed and heated for hardening (Example 620)

around the ¼-in.-diam shaft to braze the shaft to the upper and lower mounting plates, and a small amount of BCu-2 copper paste was applied at one end of the drive pin to braze it to the two mounting plates. Because of the separation between the two plates on the guide-pin side, a small amount of BCu-2 copper paste was placed on each end of the guide pin. The copper paste was applied manually. The assemblies were placed in brazing trays, with the shaft in a vertical position, and were supported in this position by ceramic spacers.

The brazing trays were placed on the mesh belt of a continuous conveyor furnace containing a dry hydrogen atmosphere and were transported up an incline to the horizontal preheat and high-heat chambers at a speed of 20 ft per hour. Because the assemblies were small, they heated to brazing temperature in about 2 min. After 8 min at brazing temperature, the assemblies were conveyed into water-jacketed cooling chambers, where they cooled rapidly in the hydrogen atmosphere to room temperature. Brazed assemblies emerged from the exit end of the furnace bright and free of oxidation.

The brazed assemblies were visually inspected 100% for complete joint coverage. Hardness tests on a sampling basis were used to determine whether the assemblies had responded properly to hardening. Tempering to the desired final hardness followed the simultaneous brazing and hardening operation. Additional brazing conditions are given in the table with Fig. 6.

Example 621 — Impeller Assembly: Furnace Brazing vs Gas Tungsten-Arc Welding (Fig. 7). The impeller shown in Fig. 7 is typical of those used in food-processing and pharmaceutical-processing equipment. Originally, the type 410 stainless steel vanes and disk were joined by gas tungsten-arc welding. Because type 410 is an air-hardening steel, preheating and postheating were required, to prevent cracking. In addition, the assembly required reheat treatment after welding, to obtain a hardness of Rockwell C 32 to 38. The following processing steps were required when gas tungsten-arc welding was used:

1 Degrease and clean.
2 Assemble vanes in disk.
3 Preheat assembly in oven to 450 F.
4 Weld (maintaining an interpass temperature of 400 to 450 F).
5 Postheat at 600 F for 2 hr.
6 Bright harden.
7 Temper to Rockwell C 32 to 38.

In 500-assembly lots, the cost of these operations to the manufacturer was approximately $3.75 per assembly, and the production rate was low.

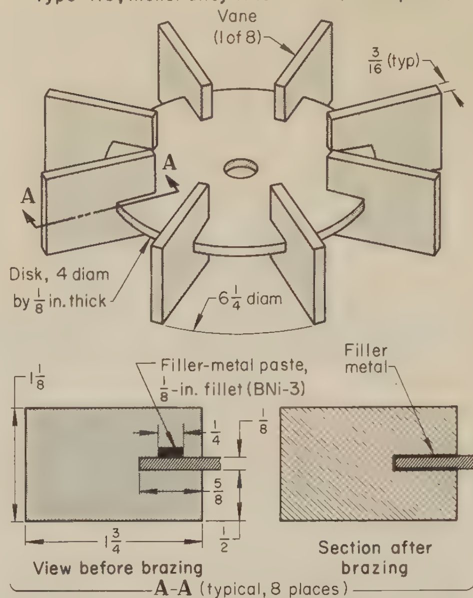
A change to furnace brazing reduced cost to $0.95 per assembly, increased the production rate, and also eliminated the need for a separate hardening operation. The sequence of steps for combined furnace brazing and hardening was:

1 Degrease and clean.
2 Assemble vanes in disk.
3 Apply BNi-3 filler-metal paste to one area of each joint.
4 Braze and harden in the same operation.
5 Temper to Rockwell C 32 to 38.

After the components had been vapor degreased, the vanes were assembled in the disk, using an assembly fixture and a small hand-operated arbor press (a light interference fit made the assembly self-jigging). Then a ⅛-in. fillet of filler-metal paste was applied by air applicator to a ¼-in.-long area on each vane where the vane and disk intersected (see section A-A in Fig. 7).

Assemblies were loaded on a 12-in.-wide continuous mesh belt and conveyed into the furnace, where they were brazed and austenitized at 2000 F, under protection of dry hydrogen. The assemblies emerged from the cooling chamber bright and clean, fully hardened, and with completely uniform brazed joints between all vanes and the disk. Assemblies were then ready for tempering. Inspection was 100% visual. Additional brazing conditions are given in the table with Fig. 7.

Type 410; nickel alloy filler metal (BNi-3 paste)



Furnace Brazing in Dry Hydrogen

Furnace	Continuous conveyor(a)
Furnace temperature	2100 ± 10 F
Brazing temperature	2000 ± 10 F
Hydrogen dew points	—100 F (incoming); —70 F (exhaust)
Hydrogen flow rate	400 cu ft per hour
Filler metal	BNi-3 paste(b)
Time at brazing temperature	5 min
Cooling	In hydrogen atmosphere
Production rate	120 assemblies per hour

(a) Electrically heated (60 kw), constructed with heating chamber (6 in. high, 12 in. wide, 36 in. long) higher than entrance and exit ends. (b) Paste consisted of 80% BNi-3 powder and 20% acrylic resin with acetone thinner.

Changing to furnace brazing from gas tungsten-arc welding decreased cost per assembly by about 75%, increased production rate, and eliminated the separate hardening operation.

Fig. 7. Impeller that was simultaneously furnace brazed and hardened (Example 621)

The cost of producing similar impeller assemblies from type 321, an austenitic grade of stainless steel, by furnace brazing in dry hydrogen and by gas tungsten-arc welding was as follows:

Furnace brazing	$0.91 each
Gas tungsten-arc welding	$3.15

In almost any joining application involving small parts, the advantage of brazing over welding is likely to increase as the number of joints increases. For instance, in this application, if the number of vanes per impeller were doubled, the advantage of brazing would increase proportionately.

Example 622. Brazing Stainless Steels to a 12.5% Cr Turbine-Quality Steel (Fig. 8)

The assembly shown in Fig. 8 is typical of the design of impellers used in turbo-compressors. The function of the impeller was to raise the pressure and temperature of the gas passing through the compressor. Impeller speeds ranged from 3000 to 30,000 rpm. The stainless steel impeller blades were used instead of aluminum alloy blades where the working temperature was unusually high, or where the gases passing through the compressor were especially erosive or corrosive.

Brazed impellers were preferred to cast impellers because the cast product entailed extremely high pattern costs, could not be salvaged when defective, and resulted in a rejection rate that was 75% above that of the brazed impeller.

The brazed impellers were made by copper brazing 20 curved blades of type 403 stainless steel to a cover plate, and to a hub plate and type 304 blade-locating pins that were inserted in the hub plate and were also brazed to it. The locating pins were made of wire that was sheared to desired length in a special fixture, and then cleaned by washing in acetone. The hub plate and cover plate were made of a turbine-quality stainless forging steel of the following composition: 0.06 to 0.13 C, 0.25 to 0.80 Mn, 12.0 to 13.0 Cr, 0.50 max Si, 0.03 max P, 0.03 max S, and 0.50 max Ni.

Blades were made from a formed cylinder, the seam of which was welded by the shielded metal-arc process using an E308-16 electrode. The welded cylinder was then stress relieved at 1300 to 1350 F for 1½ hr per inch of section and cooled in still air. The cylinder was then rough and finish machined and the blade sections were sawed out and finish machined. Width of the blades was held within 0.001 in. TIR in a set. Each blade was then drilled in two places to accommodate locating pins. The hub plate and cover plate were rough and finish machined to a finish of 125 micro-in. on the brazing surfaces and held to a flatness within 0.001 in. Top and bottom brazing strips (filler-metal preforms) were stamped from oxygen-free copper strip (99.95% Cu; equivalent to BCu-1), cold rolled to the half-hard temper. The top brazing strip had four integral tabs that, when bent, held it on the blade (see detail A and section B-B, Fig. 8).

Before assembly, the hub plate, cover plate, blades, and brazing strips were vapor degreased with a spray of trichlorethylene. Then the brazing surfaces of the hub plate, cover plate and blades were grit blasted with SAE G18 steel grit, after which these components were again vapor degreased in trichlorethylene. Finally, all components, including the brazing strips, were cleaned with acetone.

Assembly, brazing and heat treatment were done in the following sequences:

Assembly

1 Six ceramic blocks were placed in the bottom half of a type 304 box-type retort (Fig. 8) and arranged to provide the hub plate with uniform support above the bottom of the retort.
2 The hub plate was positioned on the ceramic blocks.
3 Forty blade-locating pins (two per blade) were inserted in pilot holes in the hub plate.
4 Bottom copper brazing strips were placed over the locating pins.
5 Blades were positioned over bottom brazing strips on locating pins.
6 Top copper brazing strips were placed on the blades and secured by bending tabs on the strips down on blade foils (detail A and section B-B in Fig. 8).
7 The cover plate was set into position, and held by means of locating clamps.
8 Two thermocouples were threaded through the thermocouple conduit in the bottom half of the retort (see Fig. 8), and welded to the cover plate at diametrically opposite locations corresponding to the front and back of the furnace. Thermocouples were made by threading one bare Chromel wire and one bare Alumel wire through oval, double-hole ceramic insulator sleeves. The work end of each thermocouple wire was welded to form a terminal bead, using the gas tungsten-arc process. Extreme care was taken to avoid pickup of foreign metal when forming the bead.
9 The retort cover was placed in position, and the flanges of the cover and bottom half of the retort were seal welded.
10 A soap-bubble test for leakage was applied to the seal weld, using argon pressure.

Brazing

1 The retort was purged for 5 min with high-purity argon at 75 cu ft per hour.
2 The argon was shut off and hydrogen was turned on. Hydrogen was circulated through the retort at 75 ± 5 cu ft per hour until the gas leaving the retort had a dew point of —75 F or lower. Hydrogen was circulated at this rate throughout brazing.
3 The retort was placed in a preheated furnace (1150 ± 50 F).
4 Impeller temperature was brought to 1150 ± 50 F and held for 30 min.
5 Impeller temperature was raised to 2050 to 2075 F and held for 25 min.
6 Furnace was turned off, and cooled with a blower until impeller temperature reached 1700 F.

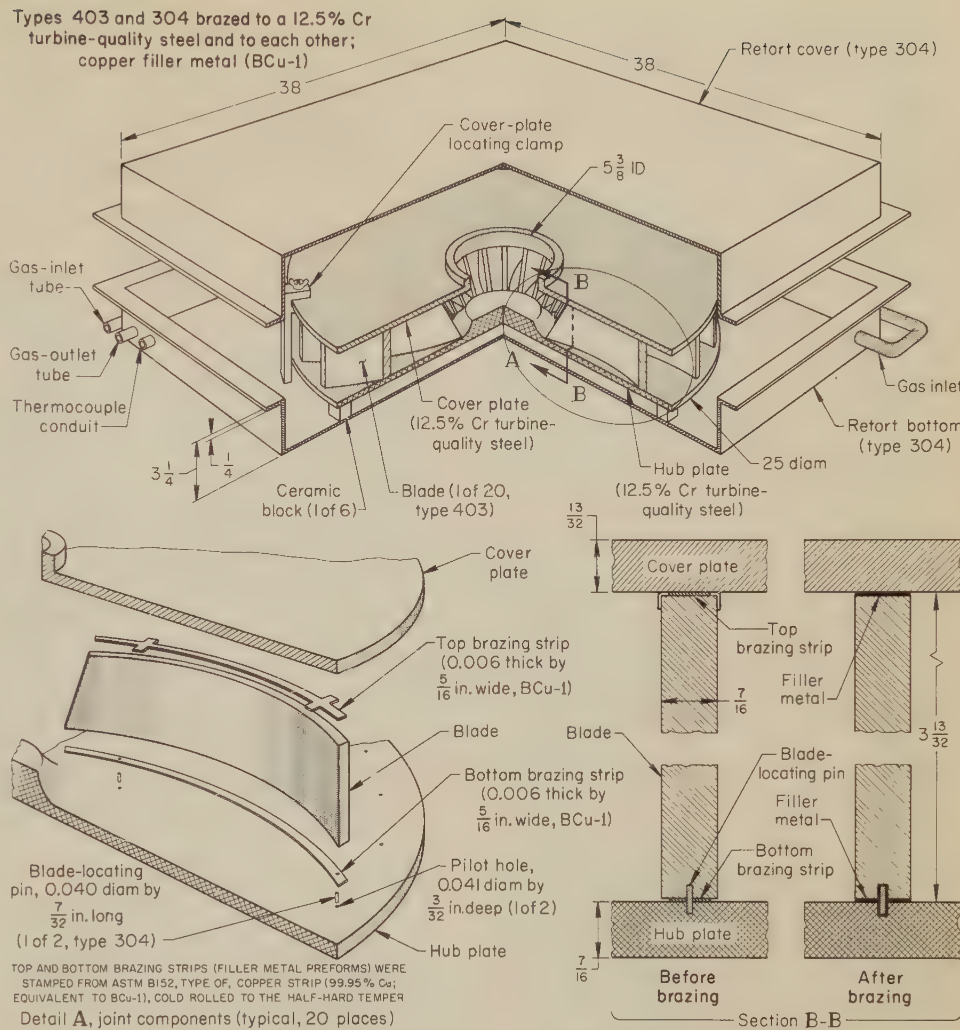
7 Furnace door was opened, and impeller was cooled to 1100 F.
8 Retort was removed from furnace, and impeller was cooled to 300 F.
9 Hydrogen being fed to retort was shut off, and retort was purged for 5 min with argon at 75 ± 5 cu ft per hour.
10 Retort was opened by grinding away the seal weld, and the impeller was removed.
11 Impeller was visually inspected to check braze quality; no visible voids or cracks were allowed.

Heat Treatment

1 Impeller was heated in inert atmosphere at 1775 to 1800 F for 1 hr.
2 Impeller was cooled in inert atmosphere to 200 F.
3 Impeller was reheated (tempered) at 1100 F (air atmosphere) for 1 hr, and then cooled in still air.

Braze quality was controlled by visual examination and dye-penetrant inspection; no voids or cracks in brazed joints were permitted. Hardness was also checked, and each impeller was subjected to a 2-min test run at 20% above the rated speed.

Additional brazing conditions are given in the table with Fig. 8.



Conditions for Furnace Brazing in Dry Hydrogen

Furnace	Box, gas fired	Hydrogen flow rate	75 ± 5 cfh(c)
Fixtures	Blade-locating pins(a)	Preheat in furnace	1150 ± 50 F for 30 min
Furnace temperature	2200 F max	Brazing temperature	2050 to 2075 F
Filler metal	BCu-1 brazing strips	Time at brazing temperature	25 min
Purging gas	Argon at 75 ± 5 cfh(b)	Postbraze heat treatment	(d)
Hydrogen dew points	—90 F (incoming); —75 F (exhaust)	Cleaning and brazing time	10.8 hr
		Heat treatment time	13 hr

(a) Pins, of type 304 stainless steel, were brazed to hub plate and blades as shown in illustration. (b) Sealed retort was purged with argon for 5 min. Argon was of 99.99% purity, with less than 0.0005% oxygen and less than 0.0002% nitrogen. Dew point was —76 F or lower. (c) Hydrogen was of 99.92% purity, with less than 0.0005% oxygen and with 0.07% max nitrogen. (d) In an inert atmosphere, assembly was heated at 1775 to 1800 F, held for 1 hr and cooled to 200 F. Then it was reheated in air to 1100 F and held for 1 hr.

Fig. 8. Impeller assembly in retort prior to furnace brazing, detail showing joint components, and section through a joint before and after brazing (Example 622)

Furnace Brazing in Dissociated Ammonia

Dissociated ammonia, when it is free of moisture and 100% dissociated, is a suitable atmosphere for brazing stainless steel with some filler metals without need for a flux. Dissociated ammonia is strongly reducing, but is less reducing than pure dry hydrogen. Consequently, although it will promote wetting action by reducing chromium oxide on the surface of stainless steel, it may not be sufficiently reducing to promote the flow of some filler metals, such as copper oxide powders. Because of its high (75%) hydrogen content, dissociated ammonia forms explosive mixtures with air and must be handled with the same precautions as those required for the handling of hydrogen.

A dissociated-ammonia atmosphere is prepared by heating anhydrous liquid ammonia in the presence of an iron or nickel catalyst. The decomposition of ammonia to form hydrogen and nitrogen begins at 600 F, and the rate of decomposition increases with temperature. Unless the atmosphere used in brazing stainless steel is completely decomposed (100% dissociated), even minute amounts of raw ammonia (NH_3) in the atmosphere will nitride stainless steel, especially the steels containing little or no nickel. In addition, because of the solubility of ammonia in water, the atmosphere coming from the dissociator must be extremely dry (preferably having a dew point of —80 F or lower). To ensure a very low dew point, the atmosphere coming from the dissociator is commonly processed in a molecular-sieve drier. To avoid oxidation of base metal and filler metal, the atmosphere must be kept pure and dry while it is inside the furnace.

Examples of Practice. In the two examples of production practice that follow, dissociated ammonia was used successfully in the furnace brazing of ferritic, austenitic and precipitation-hardening stainless steels.

Example 623. Brazing With BAg-19 Filler Metal in Dissociated Ammonia Without Flux (Fig. 9)

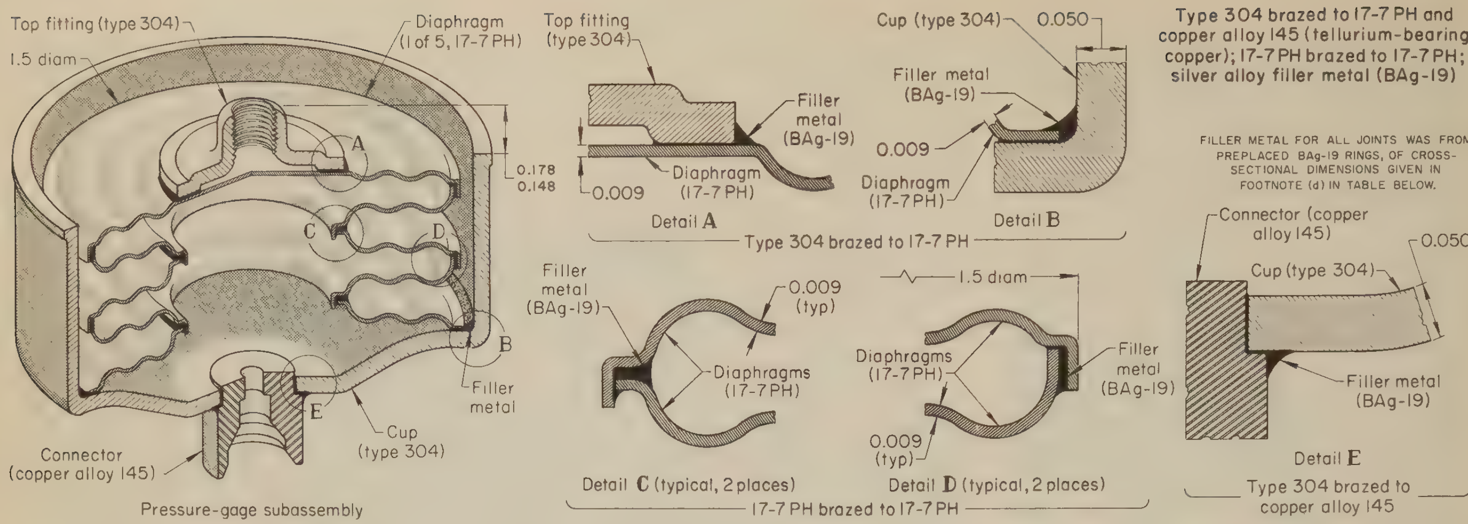
The pressure-gage subassembly shown in Fig. 9 was composed of five diaphragms of 17-7 PH stainless steel, a deep drawn cup and a top fitting of type 304 stainless steel, and a connector of copper alloy 145 (tellurium-bearing copper). Originally, these subassemblies were furnace brazed with a silver alloy filler metal that required a flux, and applying flux and assembling the fluxed components with gloved hands was time consuming. It was therefore decided to change to fluxless brazing in an atmosphere of dissociated ammonia; although this necessitated using a more expensive filler metal (BAg-19), its higher cost was offset by the greater productivity of each operator. In addition, subassemblies brazed with BAg-19 in dissociated ammonia exhibited fewer leaks and had improved corrosion resistance and better appearance than those brazed with the original filler metal and with flux.

Prior to brazing, the deep drawn type 304 cups were fully annealed at 2000 F. Annealing served to avoid erosive penetration of filler metal in zones of high residual stress. All components were chemically cleaned and then were assembled by hand, together with seven preplaced rings of filler metal. The assemblies were placed in holding fixtures, and the fixtures were loaded on the belt of a conveyor furnace heated to 1800 F. The cooling chamber of the furnace was cooled to below 60 F to ensure rapid cooling of the 17-7 PH diaphragms from the solution treating temperature, and thereby to combine solution treating with the brazing operation.

After brazing, the assemblies were cooled to —40 F, dried, and then heated to 950 F in dry dissociated ammonia to harden the diaphragms to Rockwell C 44 to 48.

Brazed assemblies were pressure tested in a bellows halogen leak detector by applying Freon at 75 psi and adding compressed air to bring the total pressure up to 300 psi. Leakage of Freon in the gas-air mixture would have been detected by the halogen leak detector. It was required that there be no leakage at the most sensitive setting of the leak detector.

The rejection rate for leakage, based on 750,000 bellows produced, dropped from



Conditions for Furnace Brazing in Dissociated Ammonia

Furnace ....Chain-belt conveyor(a)	Filler metal ....BAg-19, preplaced rings(d)	Heating time ....5 min
Furnace temperature(b) ....1800 F	Flux ....None(e)	Cooling-chamber temperature ....60 F max(f)
Dissociated-ammonia dew point ....—80 F(c)	Furnace belt speed ....10 in. per min	Precipitation-hardening temperature ..950 F(g)

(a) Electrically heated, with elevated high-heat zone. (b) For brazing the subassembly, and simultaneously solution heat treating the 17-7 PH diaphragms. (c) Achieved by running the dissociated ammonia through a molecular-sieve drier after cracking.

(d) Cross-sectional dimensions (and product forms) of filler-metal rings were as follows: for joint between diaphragm and top fitting (detail A), 0.050 in. wide by 0.004 to 0.005 in. thick (stamping); for outside joints between diaphragm segments (detail D) and joint between diaphragm and cup (detail B), 0.040 in. wide by 0.004 to 0.005 in. thick (ribbon); for inside joints between diaphragm segments (detail C), 0.030 in. wide by 0.005 in. thick (ribbon); and for joint between cup and connector (detail E), 0.060 by 0.010 in. (wire). (e) Use of BAg-19 eliminated the need for flux, which had been required with the silver alloy filler metal originally used.

(f) To cool rapidly from 1800 F and ensure solution treatment of the 17-7 PH diaphragms. (g) In dry dissociated ammonia, after subassembly had been cooled to —40 F and dried. The 17-7 PH diaphragms were hardened to Rockwell C 44 to 48.

Fig. 9. Pressure-gage subassembly for which furnace brazing was combined with solution heat treatment of the 17-7 PH diaphragms (Example 623)

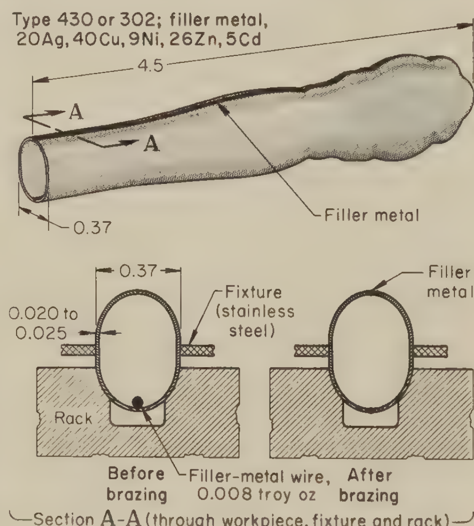
2.8% with the original silver alloy filler metal to 1.0% with the BAg-19 filler metal. Field corrosion returns dropped 96%. The decrease in rejections due to leakage saved $10,000 per year. In addition, $22,500 per year in labor and overhead was saved by the elimination of fluxing. By eliminating the stains caused by flux, it was no longer necessary to paint the assemblies. A summary of processing data is given in the table with Fig. 9.

Example 624. Use of a Special Filler Metal for Color Matching in the Brazing of Tableware Handles (Fig. 10)

To enhance the appearance of brazed tableware handles, it is desirable to match the color of the filler metal to that of the base metal, thereby de-emphasizing the brazed seam. For this purpose, a special filler metal containing 20% silver, 40% copper, 9% nickel, 26% zinc, and 5% cadmium was selected to braze the shells of stainless steel tableware handles, such as that shown in Fig. 10. This nickel-containing filler metal is not susceptible to crevice corrosion. The shells, which were made of either type 430 or type 302 stainless, were furnace brazed in a dissociated-ammonia atmosphere, using a type 3A flux.

The shell halves from which handles were made were formed and coined in a drop hammer, and flash was trimmed in a press. Trimmed edges were ground smooth on a belt grinder. Using a printing-type rubber roller, a light coating of type 3A flux was applied to the joint surfaces of each shell half. Two shell halves were then held together in a lightweight stainless steel fixture, which made contact near the middle of the shells without contacting the joints, a piece of filler-metal wire weighing 0.008 troy oz was placed inside the shell, and the shell was placed on a rack, each side of which had a series of notches into which the shells rested without contacting the joint (see section A-A in Fig. 10).

Racks were placed on the conveyor belt of an electric muffle furnace and were carried into the heating zone, where they remained for 4½ to 6 min at a temperature of about 2000 F. Shells were heated and cooled under protection of dissociated ammonia. After brazing, flux residue was removed from the shells with hot water. Additional brazing conditions are given in the table with Fig. 10.



Furnace Brazing in Dissociated Ammonia

Furnace	Muffle (electric); chain conveyor
Furnace temperature	2000 F
Filler metal	0.008-troy-oz length of wire(a)
Flux(b)	AWS type 3A
Joint preparation	Belt grinding
Brazing time	4½ to 6 min

(a) Filler metal, of composition as noted at top left in illustration, melts at 1150 F and flows at 1750 F. (b) Applied by rubber roller to joint surfaces.

Fig. 10. Brazed tableware handle for which a special filler metal was selected, for good color match (Example 624)

In 90% of the assemblies, capillary action was complete and the entire seam was satisfactorily brazed. The remaining 10% required rebrazing because of incomplete filling in the upper joint. These handles were rebrazed by turning them 180° so that the unfilled portion of the seam was at the bottom; no additional filler metal was used. Only about 1% of the rebrazed handles failed to produce an acceptable joint.

Furnace Brazing in Argon

Argon is occasionally used as a furnace atmosphere in brazing stainless steels to other stainless steels or to reactive metals such as titanium (see Example 625, which follows). Argon has the advantage of being chemically inert with respect to all metals; thus, it is a useful protective atmosphere for metals that can combine with or absorb reactive atmospheres such as hydrogen. An argon atmosphere has the disadvantage of being unable to reduce oxides; consequently, the surface of stainless steel components must be exceptionally clean and free of oxides when brazed in argon.

Example 625. Brazing of Type 347 Stainless Steel to Titanium in an Argon Atmosphere (Fig. 11)

A manufacturer of jet engines designed a gear-reduction box made of commercially pure titanium. This complicated fabrication was made from assemblies of stampings and machined forgings, most of which were joined by gas tungsten-arc welding in argon-filled welding chambers. However, for joining some assemblies brazing was more appropriate.

A typical assembly that was furnace brazed in argon is shown in Fig. 11. This assembly consisted of a machined forging of commercially pure titanium (AMS 4921), and a length of seamless type 347 stainless steel tubing that was flared or expanded for a distance of approximately 5/16 in. to accept the titanium forging. The outside diameter of the titanium forging was held to 0.500 +0.000, −0.001 in. The inside diameter of the stainless steel tube was held

to 0.501 +0.001, −0.000 in. This allowed for a diametral clearance of 0.001 to 0.003 in. between components at room temperature. From 32 to 1650 F, the mean coefficient of expansion of commercially pure titanium is 5.7 micro-in./in./°F; from 32 to 1600 F, the mean coefficient of expansion of type 347 stainless steel is 11.1 micro-in./in./°F. Calculation of the expansion that would occur during heating both components to 1650 F indicated a 0.004-in. diametral clearance between the titanium and the stainless steel. Adding the diametral clearance at room temperature (0.001 to 0.003 in.) to the 0.004-in. clearance gave a total diametral clearance at brazing temperature of 0.005 to 0.007 in., which is within the clearance range commonly recommended for silver brazing.

Silver alloy BAg-19 was selected as the brazing filler metal, because of its high fluidity in an argon atmosphere and because its brazing temperature is lower than that of pure silver. Most alloying elements in silver brazing alloys form brittle intermetallic compounds with titanium, which result in unreliable joints. With the exception of a minute amount of lithium, the only alloying element contained in BAg-19 is 7.5% Cu, and by limiting the time at brazing temperature, sound ductile joints were made and formation of the Ti-Cu intermetallic phase was minimized.

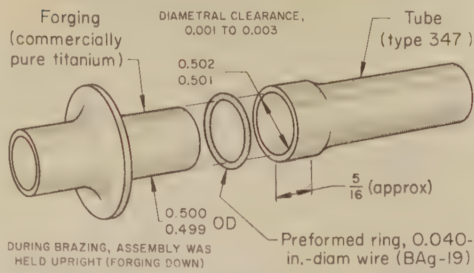
Prior to assembly, the titanium forging was degreased and cleaned in a solution containing 40% nitric acid plus 2% hydrofluoric acid. The stainless steel tubing and the filler metal (preformed rings of 0.040-in.-diam BAg-19 wire) were cleaned by washing in acetone. All subsequent handling of the components during assembly, and until after brazing, was accomplished with the operators wearing clean white lint-free cotton gloves.

The titanium forging was inserted into the expanded end of the stainless steel tube until it was completely seated. A filler-metal ring was placed around the outside diameter of the titanium tube at the joint intersection. The assembly was placed upright (forging down) in a titanium sheet-metal holding fixture and loaded into an Inconel retort. The retort was designed for displacement purging with an inlet and exit manifold for the argon atmosphere. After loading, the retort cover was seal welded to its base, using the gas tungsten-arc process.

The retort was purged for 30 min with pure, dry argon at 150 cu ft per hour, and then was placed in a gas-fired pit-type furnace. The retort was heated to 600 F and held at that temperature for an additional 30 min, or until the dew point of the exiting argon was −70 F, as recorded on an electrolytic water analyzer. The furnace temperature was then raised until the assembly temperature reached 1650 F, as indicated by a Chromel-Alumel thermocouple attached to the titanium holding fixture within the retort. As soon as this temperature was reached, the retort was removed from the furnace and fan-cooled to room temperature.

The retort cover was opened by grinding away the seal weld, and the assemblies were removed. The titanium and stainless steel components emerged bright and clean, with evidence of excellent filler-metal flow. Radiographic inspection showed over 95% joint coverage. All joints were visually inspected on both sides.

Type 347 brazed to commercially pure titanium (AMS 4921); silver alloy filler metal (BAg-19)



Furnace Brazing in Argon

Furnace	Pit, gas-fired(a)
Retort	Inconel, 24-in. diam and length
Fixture material	Titanium sheet(b)
Furnace temperature	1700 ± 10 F
Brazing temperature	1650 ± 10 F
Argon dew points	−85 F (incoming); −70 F (exhaust)
Argon flow rate (purging to cooling)	150 cfh
Filler metal	BAg-19, 0.040-in.-diam wire(c)
Time at brazing temperature	Less than 1 min
Cooling	In argon, to room temperature
Production lot per cycle	1 to 20 assemblies

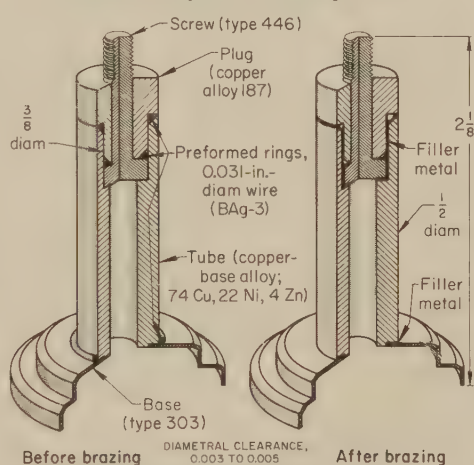
(a) 72-in. diam, 72 in. deep. (b) Holding fixture, to keep assembly upright (forging down) during brazing. (c) Preformed full ring.

Fig. 11. Stainless-and-titanium assembly (for use in a jet-engine gear-reduction box) that was furnace brazed in an argon atmosphere (Example 625)

Furnace Brazing in Air Atmosphere

The principal advantages of furnace brazing are that the process provides high production rates and provides a means for using controlled protective atmospheres at controlled dew points, often making it unnecessary to use a flux to obtain satisfactory wetting action. In most furnace brazing applications, both of these advantages are exploited. Occasionally, however, furnace brazing is selected solely on the basis of production rate, and brazing is performed without a protective atmosphere but with a suitable flux. The lower-melting filler metals are generally selected for brazing under these conditions, as in the application described in the following example.

Types 446 and 303, and copper alloy 187 brazed to copper-base alloy (74 Cu, 22 Ni, 4 Zn); type 446 brazed to copper alloy 187 (99Cu, 1Pb); silver alloy filler metal (BAg-3)



Furnace Brazing in Air Atmosphere

Furnace	Continuous belt, air atmosphere
Furnace temperature	1370 to 1450 F
Filler metal	BAg-3, 0.031-in.-diam wire(a)
Flux	AMS 3410D (AWS type 3A)
Time at temperature	1 minute (max)
Production rate	140 assemblies per hour

Furnace Brazing vs Torch Brazing

	Torch	Furnace
Production per hr, assemblies	60(b)	140
Direct-labor rate per hr	$2.40	$2.10
Direct-labor cost per assembly	$0.04	$0.015

(a) Preformed rings, preplaced as shown in illustration. (b) Based on brazing one assembly at a time, with 60-second preparation and heating time per assembly.

Fig. 12. Stainless-and-copper valve bobbin that was furnace brazed in an air atmosphere, when production quantity made furnace brazing more economical than torch brazing (Example 626)

Example 626. Substitution of Furnace Brazing in Air Atmosphere for Torch Brazing (Fig. 12)

The gas-valve bobbin assembly shown in Fig. 12 was satisfactorily brazed by both the torch and furnace processes, the choice of process depending primarily on the production rate required. The cost data given in the table with Fig. 12 are indicative of the differences in rate requirements considered. Labor costs for torch brazing were developed on the basis of a production rate of 60 assemblies per hour, whereas costs for furnace brazing were developed on the basis of a production rate of 140 assemblies per hour. The application of furnace brazing to the bobbin assembly is described in the following paragraphs.

As Fig. 12 shows, the bobbin assembly consisted of four parts: a screw made of type 446 stainless steel; a base made of type 303 stainless steel; a tube made of a copper alloy closely related to nickel silver (74 Cu, 22 Ni, 4 Zn); and a plug, made of copper alloy 187 (99 Cu, 1 Pb), which held the screw in place and blocked gas passage through the tube.

All components were thoroughly vapor degreased before brazing. They were assembled with two preformed rings of 0.031-in.-diam BAg-3 filler-metal wire; the diametral clearance on the joints was 0.003 to 0.005 in. One preform, with a ⅜-in. internal diameter, was placed over the neck of the plug; the other, with a ½-in. internal diameter, was placed over the tube adjacent to the base joint. The joint areas were coated with type 3A brazing flux, and the assemblies were brazed in a continuous-belt conveyor furnace.

Filler metal BAg-3 was chosen in preference to BAg-1 or BAg-1a to avoid the risk of interface corrosion.

Torch Brazing

For stainless steel, the fundamentals of torch brazing, as well as its advantages and limitations, are basically the same as for carbon steels (see the article on Torch Brazing of Steel, which begins on page 619). However, because of the metallurgical characteristics of stainless steel and its requirements for corrosion resistance, best results are obtained when special consideration is given to type of flame at the torch, and to filler-metal composition.

Flame Adjustment. To aid in reducing the oxide already present, as well as to prevent further oxidation of the work-metal surfaces, a strongly reducing flame should be used for torch brazing stainless steel to itself. A reducing flame is also satisfactory for brazing stainless steel to nickel alloys or carbon steels. However, when brazing stainless steel to copper alloys, some compromise is necessary. Normally, a slightly oxidizing flame is best for brazing copper. For brazing stainless steel to copper, the use of a slightly reducing flame is usually a satisfactory compromise.

Filler Metals. The silver alloy filler metals that flow at relatively low temperatures are used almost exclusively for torch brazing of stainless steels. BAg-3 is most often used, because it flows well in the temperature range of 1300 to 1400 F and provides joints that have greater resistance to corrosion

than those brazed with filler metals like BAg-1 or BAg-1a (although these filler metals are also used). The use of filler metals that require temperatures higher than about 1400 F results in excessive oxidation. Sometimes, for special applications, higher-melting filler metals must be used (see Example 615).

Flux of type 3A is used almost exclusively for torch brazing of stainless steel. It has a working range of 1050 to 1600 F, and is well suited for use with the lower-melting silver alloy filler metals. However, in some applications type 3B flux is preferred (see Example 615).

Example of Practice. The example that follows describes typical practice employed for torch brazing stainless steel to unalloyed nickel.

Example 627. Torch Brazing of Stainless Steel to Nickel (Fig. 13)

The brazed assembly shown in Fig. 13, which consisted of a type 304 stainless steel tube and a pure nickel tube, was resistance heated in service. Requirements for this assembly were as follows:

1 To transmit electricity without developing hot spots
2 To be straight and smooth, because it had to slide into a larger assembly
3 To be joined at minimum temperature, because numerous small insulated wires (not shown in Fig. 13) were in the assembly at the time of joining and were subject to damage if the joining temperature was too high.

Torch brazing with silver alloy filler metal proved to be a desirable way to make the joint, because of the relatively low brazing temperature, high electrical conductivity of the joint brazed with the silver alloy filler metal, minimum distortion, ease of removing excess filler metal, and ease of radiographic inspection.

The joint design, shown in Fig. 13, provided for preplacement of the filler metal (BAg-1a) in a ⅛-in.-wide groove machined into the shoulder of the nickel tube. The filler metal was then melted with a torch, and both filler metal and shoulder were machined to match the inside diameter of the stainless steel tube (zero-clearance fit).

For brazing the nickel tube to the stainless steel tube, several heating methods were tried, including induction heating in an inert gas, and multiple-torch heating. However, the most successful method proved to be the use of a single oxyacetylene torch by a skilled technician.

The sequence of operations for single-torch brazing was as follows:

1 Components were cleaned with acetone.
2 Flux paste was placed on the nickel tube in the area to be brazed.
3 The two tubes were assembled in a fixture with a 0.005-in. gap showing at the surface (see detail A in Fig. 13).
4 The assembly was heated with a torch until the filler metal flowed to the outside surface (flow temperature of BAg-1a is 1175 F).
5 Excess flux that flowed to the surface was removed manually.

It was possible to inspect the entire joint by making two radiographs. Only scattered porosity was detected in routine radiographic inspection of the brazed joints.

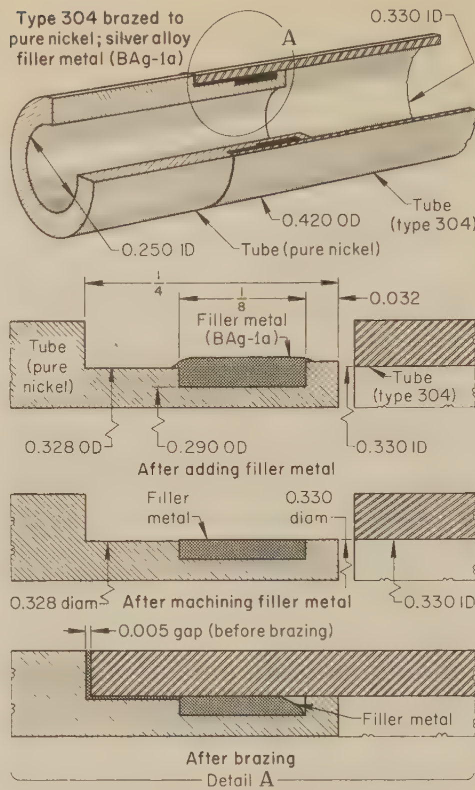


Fig. 13. Torch brazed assembly of a stainless steel tube and a pure nickel tube (Example 627)

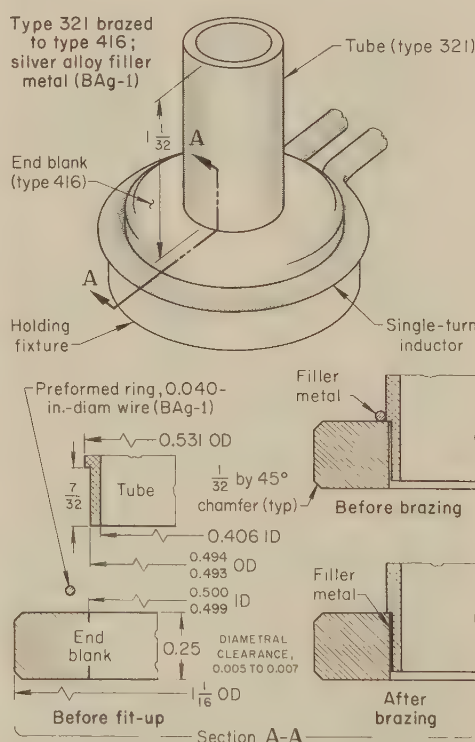
Induction Brazing

Depending on the metallurgical and physical properties of particular stainless steels, their behavior in heating by electrical induction may differ considerably from that of carbon and low-alloy steels and from that of the more widely used nonferrous metals. Further, depending on whether a stainless steel is magnetic or nonmagnetic at room temperature, the response of the steel to induction heating will vary considerably. Differences in specific heat and electrical conductivity will markedly affect response to heating by induction.

In general, because ferritic and martensitic (series 400) stainless steels are ferromagnetic at all temperatures up to the Curie temperature, they will — given the same power input — heat faster than austenitic stainless steels, which, in the annealed condition, are nonmagnetic. (Cold working may induce slight magnetism in the austenitic chromium-nickel steels, whereas the series 400 chromium steels are strongly magnetic.) Rate of heating to the temperature at which the filler metal flows will usually affect induction-coil design and coupling and may also influence selection of power-output frequency and other processing variables (see the article on Induction Brazing, which begins on page 631 in this volume).

Stainless steels may be induction brazed in an air atmosphere, using a suitable flux, although for critical applications induction brazing is sometimes done in a protective atmosphere, or in vacuum (see subsequent discussion under "Induction Brazing in Vacuum", and Fig. 16). In other applications, an inert gas such as argon may be used as a backing gas (as is often done in arc welding), to minimize oxidation (see Example 629).

Examples of Practice. The two examples that follow describe procedures used for induction brazing different types of stainless steel.



Conditions for Induction Brazing

Power supply	Vacuum tube, 20 kw, 450 kHz
Inductor	Single-turn, copper tube
Brazing temperature	1200 F
Filler metal	BAg-1, 0.040-in.-diam wire
Flux	AWS type 3A
Time at brazing temperature	10 sec
Cooling time	10 sec in fixture
Production rate	140 assemblies per hour

Fig. 14. Induction brazed assembly of tubes of types 321 and 416 stainless steel (Example 628)

Example 628. Brazing a Type 321 Tube to a Type 416 End Blank (Fig. 14)

The assembly shown in Fig. 14, part of a solenoid, consisted of a type 321 stainless steel tube brazed to a type 416 end blank. Type 321 is an austenitic stainless steel, whereas type 416 is martensitic and ferromagnetic. Consequently, although both metals were easily brazed, achieving proper joint clearance between the two components was complicated by the marked differences in coefficients of thermal expansion of the two steels. Thus, it was necessary to make calculations to determine the room-temperature clearance that would be required in order to provide suitable clearance at the brazing temperature.

Because the assembly was not intended for high-temperature service, it was preferable to select a low-melting silver alloy filler metal, BAg-1, and a relatively low brazing temperature, 1200 F, in order to minimize heating and oxidation of the stainless steel components. For brazing at 1200 F, calculations based on coefficients of thermal expansion showed that the following dimensions and tolerances in the joint area would be satisfactory: for the tube diameter, 0.494 +0.000, −0.001 in.; and for the inside diameter of the end blank, 0.500 +0.000, −0.001 in. Thus, diametral clearance at room temperature was 0.005 to 0.007 in.

The shape of the assembly and the low brazing temperature both favored brazing by induction. The end blank was in the hardened-and-tempered condition prior to brazing, and the short induction heating cycle (10 sec) did not reduce the hardness to less than the required minimum.

Prior to brazing, the components were vapor degreased. The end of the tube was dipped in flux and inserted in the end blank. A preformed ring of filler-metal wire was slipped over the tube and located at the top of the joint. Then the end blank was placed on a holding fixture and positioned in a single-turn inductor, as shown in Fig. 14, and heated for 10 sec. After

brazing, the assembly was cooled in air for 10 sec before it was removed from the holding fixture; it was then washed in hot water to remove the flux residue. Additional brazing conditions are given in the table with Fig. 14.

Example 629. Change From Torch to Induction for Brazing Ten Joints at a Time (Fig. 15)

The temperature-sensor assembly shown in Fig. 15, consisting of types 302, 303 and 304 stainless steel components, had formerly been joined by torch brazing, using an oxyacetylene torch. Torch brazing was slow, and more time was required for cleaning than for assembly. A change in design forced a change to another brazing technique, and induction brazing was chosen as the most compatible with the BAg-7 filler metal used, as well as being fast and efficient. A special fixture was used to backfill the interior of the assembly with argon during the brazing cycle.

The seven-step sequence of operations was as follows:

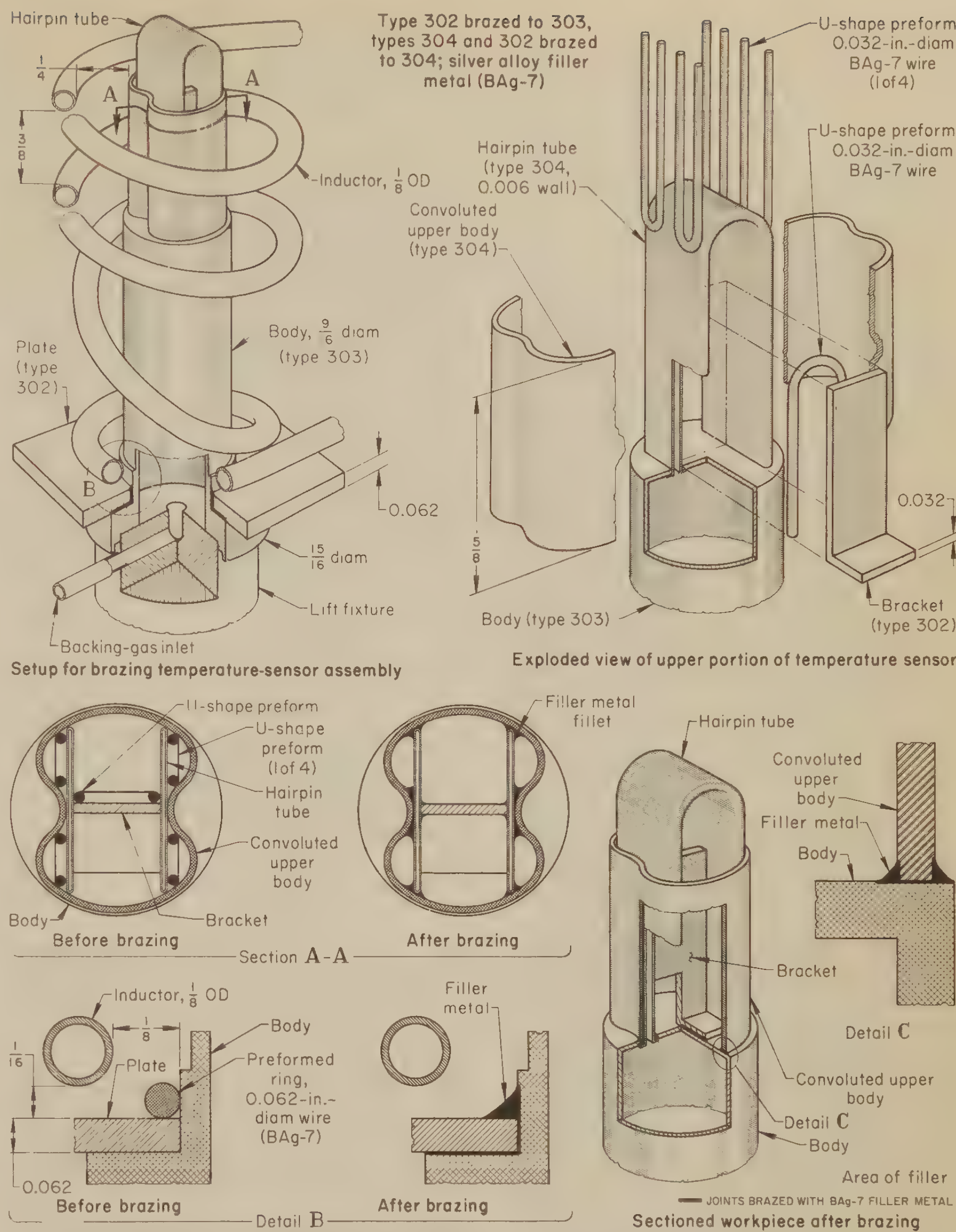
1 Components were hot vapor degreased.
2 Components were etched in an acid solution (3% hydrofluoric acid, 10 to 15% nitric acid, remainder water) at 140 F, for 1 minute (max). They were rinsed, first in a dilute solution of sodium bicarbonate, then in cold water, and finally in alcohol. They were allowed to dry and placed in a clean covered container to await assembly.
3 After assembling, the entire outside of the assembly was coated uniformly with flux, and filler-metal preforms were dipped in flux and placed in position (see Fig. 15).
4 The assembly was placed on a lift fixture and positioned in the inductor.
5 Power was turned on for 40 sec, and time then was allowed for filler metal to solidify.
6 The assembly was placed in a hot aqueous solution of sodium bicarbonate to dissolve all excess flux, then rinsed in water.
7 The assembly was placed in alcohol to remove water, then on racks to permit the alcohol to evaporate, and finally into clean plastic-covered containers.

Assembly and fluxing were delicate operations. After the parts were assembled, both ends of the rectangular-section hairpin tube were flared to keep it in position. A standard paste brush was used to paint the entire assembly with flux. This required careful application. An excessive amount of flux required too much of the brazing cycle to drive off excess moisture, and not enough time was left for brazing. Too little flux would require overheating the fragile assembly to obtain wetting.

Coil design was important in the success of this brazing procedure. The upper portion of the assembly, because of thin sections, came to brazing temperature quickly, whereas the comparatively bulky base heated more slowly. To deal effectively with these conditions, the coupling between coil and workpiece was made much closer at the base than at the top (⅛ in. per side, compared with ¼ in. per side at the top). Two turns were used at the top to spread the heat uniformly along the upper longitudinal joints, whereas a single turn at the base concentrated heat at the single flange-to-tube joint.

The argon backing gas kept the interior bright and clean during the brazing cycle. Operations previously used to remove internal scale were therefore no longer needed. The only postbraze cleaning necessary was a light bead blast to remove stains and discoloration due to handling and to give the product a better appearance.

Induction Brazing in Vacuum. A distinctive advantage of induction brazing, as applied to stainless steel, is that it lends itself to use with simple setups that permit brazing in vacuum. Closed, nonmetallic containers with reasonably good strength and dielectric properties can provide enclosure for the assembly to be brazed and can be evacuated prior to brazing. The inductor can be placed outside the container and can heat the assembly efficiently without being part of the vacuum system.



Conditions for Induction Brazing

Power supply ....Vacuum-tube type(a)	Filler metal ....BAg-7 preforms(b)
Inductor ....Three-turn, ⅛-in.-OD copper tube	Flux ....AWS type 3A
Backing gas ....Argon, at 2 cu ft per hour	Brazing time ....40 sec

(a) Rated at 700 kHz, 1.5 kw; approximately 1 kw was used for this application. (b) Five U-shape preforms of 0.032-in.-diam wire, and one preformed ring of 0.062-in.-diam wire.

Fig. 15. Setup for induction brazing a temperature-sensor assembly, using argon backing, and details of components and joints (Example 629)

Stainless steel collar-and-tube assemblies, such as that shown in Fig. 16, were brazed in a simple setup that combined induction heating and the protection afforded by heating in vacuum. The vacuum container consisted of a high-silica, low-expansion glass tube with copper end fittings, connected to a vacuum system. The collar-and-tube components, with preformed BNi-7 filler-metal rings pressed into place on the shoulder of each collar, were positioned and held inside the glass tube by means of a simple holding fixture. The tube was sealed and evacuated, with a multiple-turn inductor, outside the tube, in position to heat one of the collars. When the vacuum reached 10^{-3} torr, heating was started. The collar was heated slowly to 1775 F, and after 4 min the power was shut off. The tube was then repositioned to bring the second collar into the field of the inductor, and the heating sequence was repeated.

When the second collar had cooled to a black heat (no glow visible in normal light), the tube was backfilled for 5 min with argon. Brazed joints were inspected visually and by dye-penetrant and metallographic methods and were found to be sound and acceptable in all respects. The induction heating source was an 8-kva spark-gap con-

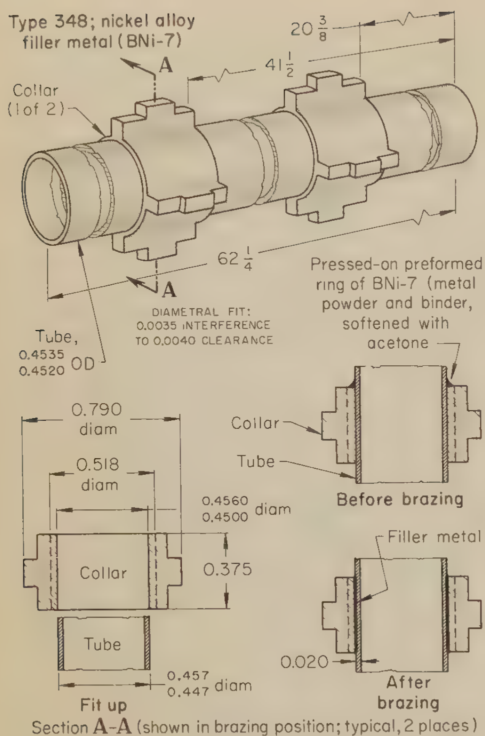


Fig. 16. Collar-and-tube assembly that was induction brazed in vacuum (see text)

verter with an operating frequency of 175 to 200 kHz. The water-cooled external inductor coil was made of ¼-in.-diam copper tubing. Production rate was 22 assemblies per day.

Dip Brazing in a Salt Bath

Brazing of stainless steel by immersion of all or a portion of the assembly in molten salt offers essentially the same advantages that would apply to brazing similar assemblies made of carbon steel, and is likewise subject to the same limitations (see the article on Dip Brazing of Steel in Molten Salt, which begins on page 655).

Example of Practice. The example that follows describes an application for which dip brazing was preferred.

Example 630. Change From Torch or Induction to Dip Brazing, To Reduce Distortion (Fig. 17)

The television wave-guide assembly shown in Fig. 17 consisted of a type 304 stainless steel flange brazed to a tube of copper alloy 230 (red brass, 85%). Satisfactory end use was dependent on a minimum of distortion. When the assembly was brazed by torch or induction, rejection rate sometimes reached 70% because of distortion caused by uneven heating. When dip brazing was adopted, the rejection rate dropped almost to zero.

Prior to brazing, the stainless steel flange was degreased and pickled, and the brass tube was degreased and bright dipped. Then the flange was placed on the tube, the tube end was flared outward slightly, a preform of the filler metal was placed over the tube adjacent to the flange, and AMS 3410D (AWS type 3A) flux was applied to the joint. The assembly was suspended flange-down over an electrically heated salt bath to preheat the flange and dry the flux. The assembly was then lowered slowly into the molten bath for a distance of about 1 in. above the flange. The molten bath was maintained at 1350 F. The assembly was held in the bath for 1½ min, and was then removed and air cooled. The flux residue was removed by rinsing the assembly in water at 140 F. Production rate was 30 assemblies per hour.

Electron Beam Brazing

Electron beam welding equipment and techniques have been used to a limited extent for brazing. The high vacuum used in the work chamber (10^{-4} to 10^{-5} torr) permits adequate flow of brazing filler metal on properly cleaned joints without using a reducing atmosphere or a flux. There is no problem of flux entrapment, and no need to clean the work after brazing. The high vacuum and the absence of flux provide a brazing environment that avoids the problems associated with prepared atmospheres when brazing some stainless steels, as well as the more reactive metals such as titanium.

Electron beam brazing is done in the same way as electron beam welding, except that the beam is defocused to provide a larger beam spot and to reduce the power density (kilowatts per square inch) or the heating effect on the work. (Electron beam welding is discussed in the article that begins on page 519.) If necessary, the beam spot diameter can be enlarged substantially, depending on the type of equipment (defocused beam; see Example 631), while providing an adequate amount of heat input for brazing. Work movement can be used if an area substantially larger than the beam spot size is to be heated, and the work can be rotated under the beam for uniform heating.

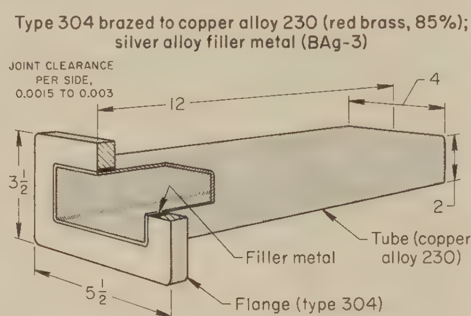
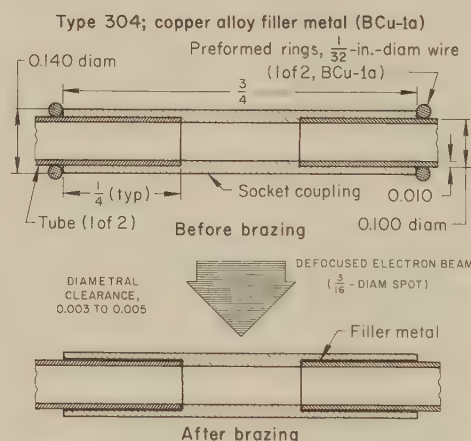


Fig. 17. Television wave-guide assembly joined by dip brazing in a salt bath, to avoid high incidence of distortion that had occurred in torch and induction brazing (Example 630)



Conditions for Electron Beam Brazing

Joint type	Cylindrical sleeve
Filler metal	¹⁄₃₂-in.-diam wire, BCu-1a
Machine capacity	3 kilowatts
Gun type	Fixed diode
Vacuum chamber	24-in. diam
Maximum vacuum	10^{-5} torr
Fixtures	Holding jig
Pumpdown time	30 min
Brazing power	18 kv, 20 to 30 ma
Beam spot size	³⁄₁₆-in. diam (approx)
Brazing vacuum	10^{-5} torr
Brazing time	30 sec

Fig. 18. Joint between two capillary tubes of an instrument package that was electron beam brazed using a low-power defocused beam in a high vacuum (Example 631)

Brazing temperatures are reached quickly, and heat can be localized to minimize grain growth, softening of cold worked metal and, in austenitic stainless steels, sensitizing of the material by carbide precipitation.

Applications. Electron beam brazing is a convenient method for brazing small assemblies such as instrument packages, combining the versatility and close controllability of electron beam heating with the advantages of vacuum brazing. Packaged devices can be encapsulated with an internal vacuum without damaging the basic package.

Tube-to-header joints in small heat-transfer equipment made of heat-resisting alloys and refractory metals are sometimes electron beam brazed. In one technique, the tube-to-header joint is electron beam welded on the top side of the header, and brazing filler metal preplaced on the reverse side of the header at the joint is caused to melt and flow by the heat of the beam.

Small-diameter, thin-wall stainless steel tubes are readily joined by electron beam brazing, as in the example that follows.

Example 631. Use of Defocused Beam for Electron Beam Brazing Small Tubes (Fig. 18)

Capillary and other small-diameter tubes used in instrument packages required leak-tight joints to be made without overheating other portions of the assembly. The use of flux also had to be avoided, since entrapped flux was difficult or impossible to remove. These conditions were met by electron beam brazing.

A typical joint in the 0.100-in.-OD by 0.010-in.-wall type 304 tubing that was brazed by the electron beam process is shown in Fig. 18. Joint design was based on the use of a ¾-in.-long socket coupling counterbored with a total clearance of 0.003 to 0.005 in. over the tube diameter and to a depth of ¼ in. Average joint clearance (per side) was therefore 0.002 in. Tubes and socket coupling were deburred and solvent cleaned, and assembled with two wire-ring preplacements of BCu-1a filler metal as shown in Fig. 18. The tubes were held in position with a small clamping fixture, and the assembly was mounted in a fixed position on a table in the vacuum chamber.

After pumpdown, the joint was brought to brazing temperature by moving the table back and forth under the defocused electron beam so that the heat of the ³⁄₁₆-in.-diam beam spot was applied chiefly to the central portion of the coupling. Heated by conduction at relatively low beam power, the filler metal melted and flowed through the joint in approximately 30 sec.

About ten assemblies were brazed, one per pumpdown, using the machine settings and other brazing conditions given with Fig. 18.

Sensitizing of the austenitic stainless steel was not a problem in this application, because the service environment was not significantly corrosive. However, the relatively short-time brazing cycle minimized grain growth, as well as dilution of the thin-wall tubing with copper filler metal.

Brazing of Aluminum Alloys

BRAZING of aluminum alloys was made possible by the discovery of fluxes that disrupt the oxide film on aluminum without harming the underlying metal, and by the development of filler metals (aluminum alloys) with suitable melting ranges and other properties.

The aluminum-base filler metals used for brazing aluminum alloys have liquidus temperatures much closer to the solidus temperature of the base metal than do those for brazing most other metals. For this reason, close temperature control is required in brazing aluminum. The brazing temperature should be approximately 70 F below the solidus temperature of the base metal, but if temperature is accurately controlled and the brazing cycle is short, it can be as close as 10 F. Aluminum alloys, depending on composition, can be brazed with commercial filler metals from 1020 to 1180 F. Most brazing is done at temperatures between 1040 and 1140 F.

Much of the equipment and many of the techniques used to prepare, braze and inspect aluminum alloys are the same as those used for other metals; the reader may refer to the articles on Furnace Brazing, Torch Brazing, Resistance Brazing and Dip Brazing of Steel in Molten Salt in this volume for general information.

Base Metals

The non-heat-treatable wrought alloys that have been brazed most successfully are the 1*xxx* and 3*xxx* series, and low-magnesium members of the 5*xxx* series. The alloys containing a higher magnesium content are more difficult to braze by the usual flux methods, because of poor wetting by filler metal and excessive penetration. Filler metals are available that melt below the solidus temperatures of most commercial wrought non-heat-treatable alloys.

Of the heat treatable wrought alloys, those most commonly brazed are the 6*xxx* series. The 2*xxx* and 7*xxx* series of aluminum alloys are low melting and, therefore, not normally brazeable, with the exception of 7072 (used as a cladding material only) and 7005.

Alloys that have a solidus above 1100 F are easily brazed with commercial binary aluminum-silicon filler metals. Stronger, lower-melting alloys can be brazed with proper attention to filler-metal selection and temperature control, but the brazing cycle must be short to minimize penetration by the molten filler metal. Sand and permanent mold casting alloys with a high solidus temperature are brazeable; the most commonly brazed are 43, 356 and 612. Formerly, aluminum die castings were not brazed because of blistering due to high gas content, but recent advances in casting technique have resulted in improved quality.

Some common wrought and cast aluminum alloys, along with their melting temperature ranges and brazeability ratings, are listed in Table 1.

Brazing of aluminum is generally limited to parts more than 0.015 in. thick, but dip brazing and fluxless vacuum brazing have been done successfully on aluminum as thin as 0.006 in.

Table 1. Melting Ranges and Brazeability of Some Common Aluminum Alloys

Alloy	Melting range, F	Brazeability(a)
Non-Heat-Treatable Wrought Alloys		
EC	1195 to 1215	A
1100	1190 to 1215	A
3003(b)	1190 to 1210	A
3004	1165 to 1205	B
5005	1170 to 1205	B
5050	1160 to 1205	B
5052	1100 to 1200	C
Heat Treatable Wrought Alloys		
6053	1100 to 1205	A
6061	1100 to 1200	A
6063	1140 to 1210	A
6951(c)	1140 to 1210	A
7005	1125 to 1200	B
Casting Alloys(d)		
43	1065 to 1170	B
356	1035 to 1135	B
A612	1105 to 1195	B
C612	1120 to 1190	A

(a) A, generally brazeable by all commercial procedures; B, brazeable with special techniques or in specific applications that justify preliminary trials or testing to develop the procedure and to check the performance of brazed joints; C, limited brazeability. (b) Used both plain and as the core of brazing sheet. (c) Used only as the core of brazing sheet. (d) Sand and permanent mold castings only.

Filler Metals

Commercial filler metals for brazing aluminum are aluminum-silicon alloys containing 7 to 12% Si. Lower melting points are attained, with some sacrifice in resistance to corrosion, by adding copper and zinc. The compositions and melting ranges of the most commonly used brazing filler metals for aluminum are given in Table 2.

The optimum brazing-temperature range for an aluminum-base filler metal not only is determined by the melting range of the filler metal and by the amount of molten filler metal needed to fill the joint, but also is limited by the mutual solubility between the filler metal and the base metal being brazed. The brazing-temperature ranges of some filler metals are related to those of some base metals in Fig. 1.

Filler metals to be applied separately from the base metal to be brazed are available as wire and sheet (thin-gage shim stock). The manufacture of filler metal in sheet and wire forms becomes more difficult as the silicon content increases. Only filler metals BAlSi-2 (alloy 4343), BAlSi-4 (alloy 4047), and alloy X4003 are available as sheet.

Most filler metals are used for any of the common brazing processes and methods, but one (alloy X4003, which contains an addition of magnesium and has a brazing-temperature range of approximately 1110 to 1130 F) has been developed exclusively for use in fluxless vacuum brazing. Another, a proprietary mixture of filler metal BAlSi-4 (alloy 4047) in powder form and a chemical compound, is used exclusively with dip

Table 2. Compositions and Melting Ranges of Brazing Filler Metals for Use on Aluminum Alloys

AWS-ASTM class	Alloy	Product form	Principal alloying elements, % Si	Cu	Mg	Zn	Approximate melting range, F
BAlSi-2	4343	Sheet, cladding	7.5	...	...	...	1070 to 1135
BAlSi-3	4145	Wire, flattened wire	10	4	...	...	970 to 1085
BAlSi-4	4047	Wire, sheet	12	...	...	...	1070 to 1080
BAlSi-5	4045	Cladding	10	...	...	...	1070 to 1095
...	X4003	Wire, sheet, cladding	7.5	...	2.5	...	1010 to 1110
...	4245	Wire	10	4	...	10	960 to 1040

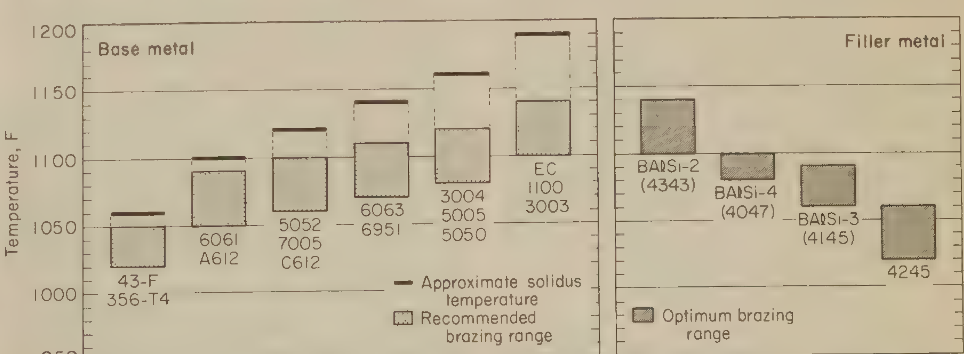


Fig. 1. Brazing-temperature ranges of some aluminum alloy base metals compared with those of four aluminum alloy brazing filler metals

Figures 1 through 8, Tables 4, 7 and 8, portions of Tables 2 and 3, and much of the text of this article are based on Chapter 13, by M. A. Miller and A. S. Russell, in Volume III of "Aluminum", American Society for Metals, 1967, p 487-524. Examples and other information were contributed by members of various Metals Handbook welding and brazing committees. The manuscript was reviewed by the ASM Committee on Welding of Aluminum Alloys.

Table 3. Compositions and Brazing-Temperature Ranges of Aluminum Brazing Sheets

Brazing sheet(a)	Sides clad	Core alloy	Cladding alloy	Cladding on each side, % of sheet thickness	Optimum brazing range, F
X3	2	3003	X4003	15% for 0.024 in. and less	1120 to 1130
				10% from 0.025 in. to 0.062 in.	...
				7½% for 0.063 in. and over	...
11	1	3003	4343	10% for 0.063 in. and less	1100 to 1140
				5% for 0.064 in. and over	...
12	2	3003	4343	10% for 0.063 in. and less	1100 to 1140
				5% for 0.064 in. and over	...
X5	2	6951	X4003	15% for 0.024 in. and less	1110 to 1115
				10% from 0.025 in. to 0.062 in.	...
				7½% for 0.063 in. and over	...
21	1	6951	4343	10% for 0.090 in. and less	1100 to 1120
				5% for 0.091 in. and over	...
22	2	6951	4343	10% for 0.090 in. and less	1100 to 1120
				5% for 0.091 in. and over	...
23	1	6951	4045	10% for 0.090 in. and less	1080 to 1120
				5% for 0.091 in. and over	...
24	2	6951	4045	10% for 0.090 in. and less	1080 to 1120
				5% for 0.091 in. and over	...

(a) Designations registered with the Aluminum Association

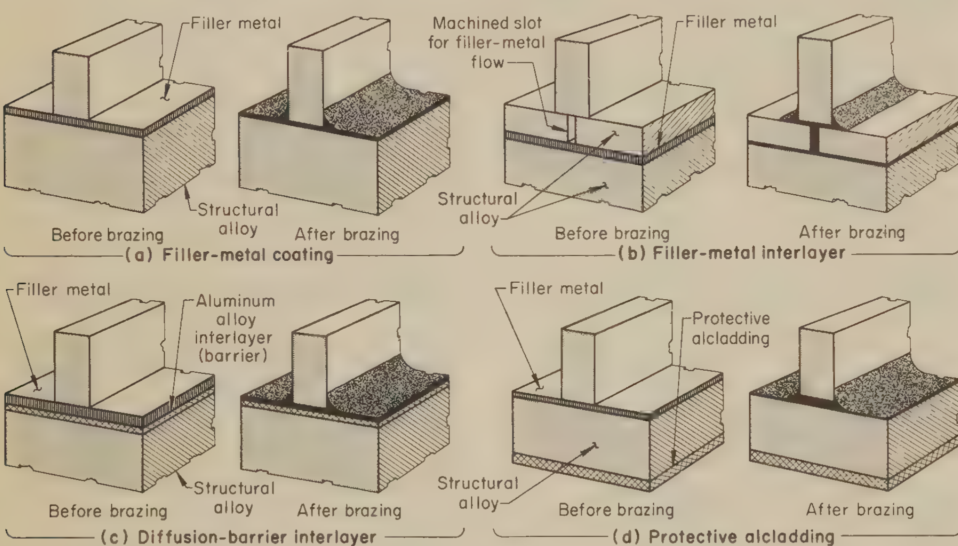


Fig. 2. Four types of aluminum brazing sheet, shown in joints with a vertical member

Fig. 3. Section showing fillets obtained with 0.040-in.-thick No. 22 brazing sheet as the vertical member in a T-joint with alloy 3003 as the horizontal member. Keller's etch. 15×.

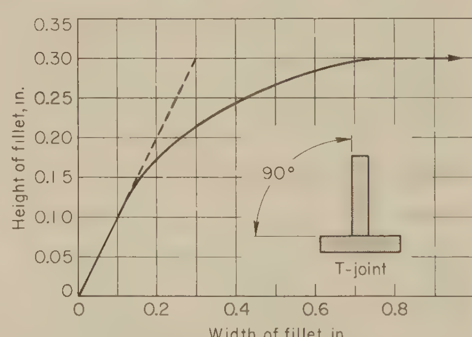


Fig. 4. Relation between height and width of fillets obtained in 90° T-joints with 0.040-in.-thick No. 22 brazing sheet as the vertical member and alloy 3003 as the horizontal member

brazing. This mixture can be brushed or extruded onto the joints and can be applied to parts in all positions. The mixture stays in place because it is baked onto the metal surface during preheating. It may be employed in brazing overhead joints in wave-guide assemblies and in applications where a small, controlled flow of aluminum alloy filler metal is desired.

Brazing Sheet

Brazing sheet consists essentially of one or more coatings or interlayers of filler metal (usually an aluminum-silicon alloy) roll bonded to one or more sheets of structural aluminum alloy. Brazing sheet provides a more convenient method of supplying the filler metal than wire, shims or powder; it is particularly convenient for mass-produced, complex assemblies. However, the choice to use brazing sheet instead of filler metal in other forms is based on cost in a given application. Brazing sheet can be subjected to drawing, bending or any other forming process that does not break the bond between the filler metal and the structural alloy that compose the sheet.

Four types of brazing sheet are shown in Fig. 2. The most common type (Fig. 2a) has filler metal on one or both sides. The compositions and brazing-temperature ranges of commercially available brazing sheets of this type are listed in Table 3.

The three other types of brazing sheet shown in Fig. 2 are available only on special order. The type shown in Fig. 2(b) has structural alloy sheets on both sides of an interlayer of filler metal; a slot is machined into the structural alloy sheet on the joint side, to permit flow of filler metal. The brazing sheet shown in Fig. 2(c) has an interlayer of aluminum alloy to act as a diffusion barrier between the high-silicon filler metal and the core sheet of structural alloy (see discussion headed "Silicon Diffusion", on page 678). The brazing sheet shown in Fig. 2(d) has filler metal on the joint side of the structural alloy and is alclad, for corrosion resistance, on the opposite side.

The structural alloys commonly used in brazing sheet are 3003, which is resistant to sagging at brazing temperatures, and 6951, which is heat treatable after brazing and is used where higher strength is desired. Some of the commercially available filler metals are used as cladding of brazing sheet.

Fluxes

Conventional brazing, performed in air or other oxygen-containing atmosphere, requires the use of a chemical flux. Fluxes, which become active before brazing temperature is reached, and which are molten over the entire brazing range, penetrate the film of oxide, exclude air, and promote wetting of the base metal by the filler metal. A satisfactory flux must (*a*) begin to melt at a temperature low enough to minimize oxidation of the parts, (*b*) be essentially molten at the time the filler metal melts, (*c*) flow over the joint and the filler metal to shield them from oxidizing gases, (*d*) penetrate the oxide films, (*e*) lower the surface tension between the solid and liquid metals to encourage wetting, (*f*) remain liquid until the filler metal has solidified, and (*g*) be relatively easy to remove after brazing is complete.

A superior flux for furnace and torch brazing will melt at a temperature only slightly lower than the melting temperature of the filler metal, ensuring uniform wetting and flow of filler alloy in minimum time. A flux to be used as a dip brazing bath is compounded to be molten and stable at the melting temperature of the filler metal. In addition, a flux for use in dip brazing should form only minimum quantities of solid particles or sludge that sink to the bottom of the bath or collect in joint interstices. Since the parts are totally immersed in flux during dip brazing and oxygen cannot reach the surfaces of the parts to re-form oxide, less active fluxes can be employed for dip brazing than for torch or furnace brazing. Physical properties of typical fluxes are given in Table 4.

Fluxes for use in brazing aluminum alloys usually consist of mixtures of alkali and alkaline earth chlorides and

fluorides, sometimes containing aluminum fluoride or cryolite ($3NaF \cdot AlF_3$). The compositions are adjusted to give a favorable balance between melting range, density, chemical activity, etching characteristics, and cost. Small amounts of one or more of the chlorides of antimony, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, silicon, tin, zinc, precious metals, or rare earths improve the performance of fluxes. Absence of fluoride prevents effective oxide removal, but too high a concentration results in an undesirably high melting range.

Flux is received in dry powder form in sealed, moistureproof containers. It can be stored for long periods if the seal is maintained. Once a flux container is opened, the utmost care must be taken to prevent contamination of the flux. Flux containers should be of perfectly clean aluminum, glass or earthenware — *never* of steel.

Aluminum brazing fluxes can be applied dry, or they can be mixed with tap water or alcohol and be applied by painting, spraying or dipping. Dry flux can be sprinkled on the work, or a heated filler rod can be dipped into the dry flux. Although flux can be mixed with tap water to form a paste, the use of alcohol may be preferred in some applications. Where vapor pressure from drying flux may cause dislocation of the filler metal or the assembly, the use of alcohol will minimize this effect.

Although 45 minutes can be considered as the maximum time lapse between the application of flux and subsequent brazing, it is recommended that the flux be applied immediately prior to brazing. When wet flux mixtures are used, they should be freshly prepared (at least once in each shift).

The wetting action of a flux can be improved considerably by the use of a wetting agent. A mixture of two-thirds flux and one-third water by weight usually is satisfactory for painting. Spraying or dipping will require a thinner consistency with more water being added. The amount of water needed to suit the spray gun used is best determined by trial.

Flux Stop-Offs. Sometimes it is desirable to take positive action to prevent filler metal from flowing beyond a certain area. Stop-offs suitable for this purpose usually consist of a mixture of equal parts by weight of a medium-heavy engine oil (SAE 30), finely powdered graphite, and benzene or naphtha (mineral spirits). Often, a mark made by a soft graphite pencil is an effective stop-off. Proprietary, commercial stop-off compounds are also available. Some of these may be applied in paste form without being baked, and later may be removed by brushing.

Furnace and dip brazing frequently require the use of a stop-off to prevent the jigs and fixtures from being brazed to the work. The mixture is brushed or sprayed on the areas to be stopped off and then baked at 400 to 600 F to carbonize the oil. One application will usually last for several brazing cycles. Stop-offs for fluxless vacuum brazing are usually refractory oxides, which are sprayed on the jigs and fixtures, or are formed on them by heating to high temperature in an air atmosphere.

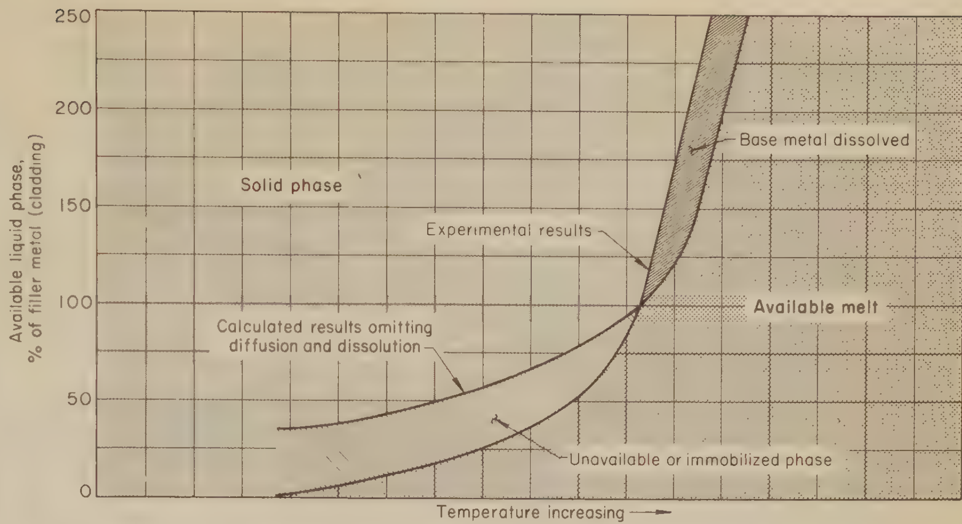


Fig. 5. Effect of temperature on availability of liquid phase from aluminum brazing sheet. See text for discussion.

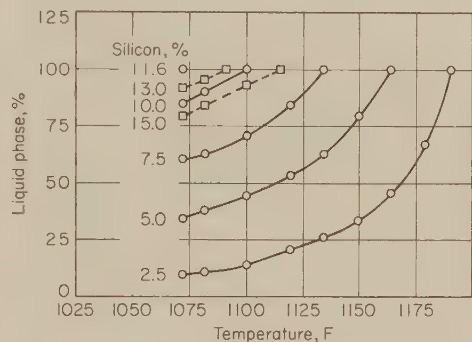


Fig. 6. Effect of temperature and silicon content on percentage of liquid phase available, for aluminum-silicon alloys (calculated)

Table 4. Physical Properties of Typical Fluxes for Brazing Aluminum Alloys

Property of flux	Dip brazing (Flux 33)	Torch and furnace brazing (Flux 34)
Solidus temperature, F	900	915
Liquidus temperature, F	1035	1115
Density at 1100 F, lb per cu ft	104	107
Specific heat, Btu per lb per °F (approximate)	0.2	(a)
Heat of fusion, Btu per lb (approximate)	168	(a)
Heat requirement, Btu to heat 1 lb of flux from solid at 70 F to liquid at 1150 F (approximate)	385	(a)
Resistivity, ohm-cm at:		
1080 F	0.43	(a)
1130 F	0.36	(a)
1150 F	0.33	(a)
1180 F	0.29	(a)

(a) These properties are not pertinent to torch and furnace brazing.

Such coatings generally last until mechanically damaged. In torch brazing, the use of stop-offs is not required, because the operator has adequate control over the flow of filler metal.

Fillet Formation

The major requirement of brazing is to adjust conditions so that gravity and capillarity cause molten brazing filler metal to flow through the full length of the joint and form fillets. The effects of gravity are often influenced by the buoyant action of molten flux, as in dip brazing. The density of the molten flux is usually only slightly less than that of molten filler metal.

In an inert gas or in vacuum, the surface tension of some aluminum brazing alloys is about 850 dynes per centimeter; in the presence of a brazing flux, it is about 650 dynes per centimeter. The addition of metallic wetting agents, such as the magnesium that is alloyed in X4003 filler metal, will effectively lower the surface tension to the range of 500 to 700 dynes per centimeter, without the presence of a brazing flux.

The microsection shown in Fig. 3, taken through a T-joint in which the vertical member was No. 22 brazing sheet (both sides clad with filler metal), shows the two fillets of filler metal to have the shape of almost perfect arcs of a circle. In an experiment on T-joints of this kind, fillet heights and widths were measured; the results are plotted in Fig. 4. As Fig. 4 shows, fillet heights and widths were equal up to approximately 0.15 in.; beyond that point, as the width increased, the height approached a maximum value of 0.30 in., which agrees with the value calculated from the surface tension.

In another experiment, T-joints in which the *horizontal* member was brazing sheet, clad on the joint side with filler metal, were heated to various temperatures, and the amount of flow of filler metal was measured. The results are shown in Fig. 5, together with the results of calculations based on the known character of the filler metal. These experimental data show that at a certain temperature, 100% of the filler metal (cladding) will flow. This is the point at which the dissolution of the base metal by the filler metal is equal to the absorption of filler metal by the base metal. As the temperature rises above this point, the molten filler metal dissolves more base metal from the brazing sheet, causing an increase in the amount of molten phase until, at the melting point of the base metal, all of the brazing sheet is molten.

As the temperature is lowered from the point indicating 100% flow, more and more of the molten phase is im-

mobilized by capillary forces in the increasing number of solid particles, and the flowability of the molten phase decreases. The temperature of 100% flow depends on composition and thickness of filler-metal cladding and base-metal core, specific flux used, type of joint to be brazed, length of the flow path, and time at temperature.

Figure 6 gives the calculated percentage of liquid phase available at several temperatures for aluminum-silicon filler-metal alloys of various silicon contents. The amount of liquid phase, of course, increases with silicon concentration up to the eutectic composition (11.6%), and with temperature. Although the eutectic composition at first appears to be optimum for filler metal, commercial practice usually employs a lower-silicon filler metal. This permits control of fillet size by temperature control, as the amount of filler metal melted depends on temperature. Figure 7 shows the amount of filler metal that flows from the interlayer of a sheet. Although from Fig. 6 all of an Al-10Si filler metal should be available for flow at 1100 F, only 25% flow was actually found in the experiment.

Silicon Diffusion. A limitation to the general application of brazing sheet is imposed by diffusion between the core metal and the coating of filler metal. Long heating times increase diffusion of silicon from the coating into the core, which can lower the mechanical properties of the core and can reduce the amount of filler metal available for flow. Figure 8 shows temperature and duration of heating for the production of 0.0005 and 0.0015-in. silicon-depleted zones in coatings of alloys Al-7.5Si and Al-12Si on brazing sheet. Brazing sheet clad with Al-7.5Si heated at 1040 F for 9 hr is shown as having a depleted zone of 0.0015 in. Thus, in theory, 0.015-in. No. 11 and 12 brazing sheets, which have a nominal cladding of 0.0015 in., could not be brazed if subjected to this temperature for this long a time, because all the silicon would have diffused into the core. When a No. 12 brazing sheet was heated for 3 hr at 1065 F, the measured thickness of the silicon-depleted zone was 0.0011 in. For Al-7.5Si cladding, Fig. 8 predicts 0.0014 in.

To restrict diffusion, the brazing cycle should be as short and at as low a temperature as possible. Core alloys must be selected to prevent formation of harmful intermetallic compounds. Under conditions where the core material is aggressively penetrated by the coating alloy, an intermediate protective layer of commercial-purity aluminum or of an alloy not easily penetrated by the coating can be used.

Joint Design

Joints to be brazed with the use of flux must be designed to permit application of the flux to the joint surfaces before assembly or to permit entry of the flux between the components after assembly. In addition, provision must be made for the flux to flow out; entrapped flux is a potential source of corrosion. Joint design must also permit the escape of gas and allow subsequent penetration by the filler

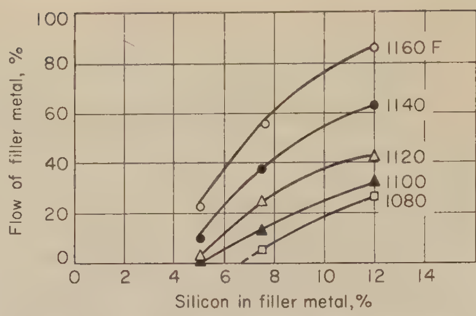


Fig. 7. Flow of filler metal from interlayer of brazing sheet (measured)

metal, and must ensure the complete distribution of filler metal in the joint. (See the section on Joint Fit and Design on page 607 in the article on Furnace Brazing.)

Assemblies to be brazed may be designed with many types of joints. For brazing processes that require a flux, joint strength equal to the strength of the base metal can be obtained with lap joints. The designs of six lap joints for brazing are contrasted with counterpart butt, T and corner joints used for welding in Fig. 31 in the article on Furnace Brazing (see page 610). Lap joints that require the filler metal to flow long distances should be designed so it flows in one direction only, because filler metal flowing from both edges of such joints may entrap flux. (The need for flow in joints having wide laps is nullified by using brazing sheet as one of the members.)

Butt and scarf joints will not usually be as strong as the base metal, but when correctly designed, such joints may give satisfactory service. For fluxless brazing processes, joints having narrow or line contact are preferred to joints having wide contact.

Joints of short length or line contacts are highly desirable during any aluminum brazing process, whether torch, furnace or dip. For long lap joints, corrugations can be used to provide an outlet for molten flux, and the final result is the same as when line contacts are used.

In joints for furnace and torch brazing, capillary rise is limited to about ¼ in. and must be considered in the design of the joint. In joints for dip brazing, capillary rise is seldom a limiting factor in design.

During brazing of aluminum, base metal and filler metal are mutually soluble. This causes the filler metal to change progressively in composition as it flows in joints, which progressively raises the liquidus temperature of the filler metal and reduces the ability of the filler metal to wet and flow. Clearances must be sufficient to prevent premature solidification of the filler metal in small capillary spaces, which entraps flux and causes porosity. The longer the distance the filler metal must flow, the greater the clearance must be.

In dip brazing with preplaced filler metal, joint clearance at room temperature ranging from 0.002 to 0.004 in. may suffice for narrow laps (¼ in. or less). Wider laps may require clearances up to 0.010 in. For furnace and torch brazing, clearance ranging from 0.004 to 0.010 in. is required for narrow laps (¼ in. or less), and as much as 0.025 in. for wider laps. With brazing sheet, clearances may be smaller. To ensure formation of a continuous fillet in fluxless vacuum brazing with brazing sheet, clearances normally should not exceed 0.003 in., but in some applications continuous fillets have been formed in joints with clearances as great as 0.009 in.

Tube-to-tube joints to be torch or furnace brazed require that the outer tube be flared 10° to 12° to produce sound joints. In joining fittings to a tube, knurling of the tube or fitting will permit complete penetration through the joint to be achieved.

When not employing brazing sheet, the correct preplacement of the filler metal is of utmost importance. Gravity is usually sufficient to keep the filler metal in place for fixed-position furnace brazing. In dip brazing, the filler may have to be held in place, because of the buoyancy of the molten flux.

Prebraze Cleaning

Oil and grease must be removed from components of assemblies to be brazed. For non-heat-treatable alloys, vapor or solvent cleaning is usually adequate, although chemical cleaning may be required for components that have been severely formed, as by spinning. For the heat treatable alloys, chemical cleaning is usually necessary, to reduce the amount of tenacious oxide film. (Chemical cleaning is not normally required for fluxless vacuum brazing.) Scrubbing with steel wool, abrasive cloth or a power-driven wire brush (preferably with stainless steel bristles) can also be used. Burrs should be removed before brazing.

Chemical cleaning methods used prior to brazing include nitric acid, hydrofluoric acid, or nitric-hydrofluoric acid mixtures at room temperature. A widely used method is immersion for about 30 sec in a solution containing equal parts of commercial nitric acid and water, followed by rinsing in clean water (preferably hot) and drying in hot air.

Aluminum-silicon alloys require a special etchant, because the silicon constituent is not attacked readily by many alkaline or acid solutions. For these alloys, a room-temperature solution of 3 parts concentrated nitric acid and 1 part concentrated hydrofluoric acid is employed. This solution requires a tank lined with an inert material such as carbon brick or certain types of plastic. The presence of fluorides necessitates caution in handling and special waste-disposal procedures. For thick and resistant oxide coatings, immersion for about 30 sec in a warm (150 F) aqueous solution of 5% sodium hydroxide is recommended. To remove the surface smut produced by this treatment, the treatment should be followed by a cold-water rinse, immersion in a room-temperature solution containing equal parts of commercial nitric acid and water, a final water rinse (preferably, hot), and hot-air drying.

Chemical cleaning of aluminum provides excellent surfaces for brazing. Cleaning in a caustic solution is par-

ticularly effective, although residues from caustic solutions can interfere with brazing — probably because of the large amounts of aluminum oxide formed. Nitric, sulfuric and phosphoric acid residues may prevent brazing entirely. To eliminate the possibility of harmful residues, chemical treatments should be followed by a hot water rinse, after which the components are dried. Hydrofluoric acid residues are not detrimental to brazing, but hydrofluoric acid is ineffectual for removing oil and grease and thus is useful only on components that have been degreased by a solvent or emulsion cleaner.

For best results, brazing should be done immediately after cleaning, or at least within 48 hr. However, if precautionary measures are taken to prevent their contamination, adequately cleaned components do not lose brazing qualities even in several weeks.

See pages 611 to 616 in Volume 2 of this Handbook for more information on methods for cleaning aluminum alloys.

Assembly

Components to be brazed must be correctly located during assembly and be held in position by some type of jigging. Correct jigging is of particular importance in dip brazing, where the displacement of air and the buoyancy of the flux must be considered. Self-jigging, when possible, offers an economic advantage over the cost of design, maintenance and replacement of jigs. Several methods of self-jigging are described and illustrated in the article on Furnace Brazing. Another method (tabs and mating slots) is described in Example 632, on the next page.

Mating surfaces of brazing sheet should not be spot welded for self-jigging, because they can separate in the flux bath. Jigs that may be required to hold the parts in correct alignment must be resistant to the highly reactive molten flux. Low-carbon steel fixtures may have sufficiently long life for a specific job. Aluminum-coated steel has longer useful life.

Because of differential thermal expansion, the aligning jig should be designed with spring relief. Stainless steel and Inconel X-750 are both good materials for such springs; Inconel X-750 will retain more of its spring characteristics at brazing temperatures. Inconel X-750 also has better resistance to corrosion, not only during brazing, but also in postcleaning operations.

Dip Brazing

The best method of heating and fluxing aluminum joints simultaneously is to immerse the entire assembly in a bath of molten flux. This is known as dip brazing, or flux bath brazing. Dip brazing has been used successfully in the manufacture of complex, multiple-joint heat exchangers.

Immersing the entire assembly into molten flux has many advantages. Heat is applied to all parts simultaneously and uniformly. Air is replaced by a buoyant and surface-active environment, promoting brazing filler-metal flow. The uniform temperature permits production assembly of parts with dimensional tolerances as low as ±0.002 in. or even less.

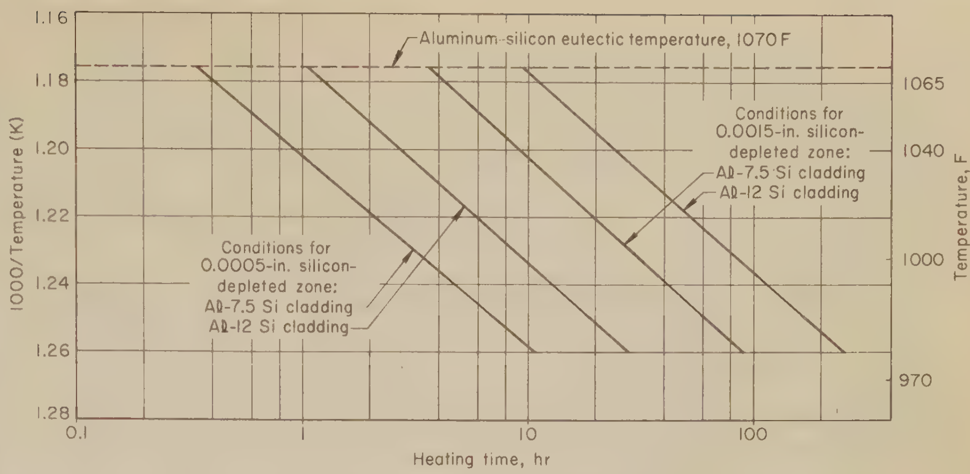


Fig. 8. Effect of heating time, temperature and original silicon content on thickness of silicon-depleted zone in filler-metal cladding

Heat-transfer units assembled from alternate corrugated and flat aluminum brazing sheets or from various crimped and formed pieces are examples of the type of work that dip brazing can handle advantageously. Units weighing up to 20,000 lb have been joined by dip brazing. Certain designs have to withstand a service pressure of 650 psi. Brazing sheet is essential to this type of work, reducing assembly and brazing costs. The rapid and even heating and flux buoyancy minimize distortion.

For assemblies designed with components in close proximity, flux removal can be tedious and expensive. For instance, when components such as those of a heat-exchanger matrix are spaced closer than ⅛ in., the flux holds to the surfaces by surface tension and capillary action; it will not drain from the components freely. This is not as great a problem with spacings greater than ⅛ in. between components of normal length; wider spacing of long components is desirable.

Equipment for dip brazing may be as simple as a heat-resistant glass beaker inside a resistance-heated furnace, or as complex as a large steel vessel lined with high-alumina, acid-proof brick. For adequate resistance to flux, the alumina content of lining brick should be at least 40%. The molten bath is usually heated by low-voltage alternating current passing through the flux between wrought nickel, Inconel 600, or carbon electrodes. These show less attack than copper or copper-bearing electrodes, and cause minimum contamination of the flux. Attack at the electrode-flux-air interface has led to preference for submerged electrodes. The bath temperature should be controlled within ±5 F.

Technique. The amount of flux to fill the bath is about 100 lb per cubic foot. Approximately 385 Btu per pound is required to melt and heat the flux. Thermocouples enclosed in protective tubes should be used to determine the bath temperature, which is the actual temperature of the assembly. There should be enough flux so that the temperature does not drop more than 5 to 10 F when parts are immersed. The specific heat of dip brazing flux, approximately 0.2 Btu per pound per °F, is about the same as that of aluminum. For assemblies that have been preheated to 1000 to 1050 F before immersion in the salt bath, there should be about 16 lb of molten flux per pound of aluminum. With this ratio, the bath temperature may drop 2 to 5 F, and it should be possible to braze four to six loads per hour.

The composition of the flux in the bath should be adjusted periodically by fluoride and chloride additions. Proprietary additive mixtures are available for this purpose. Even when the molten bath is idle, side reactions reduce its activity. Because molten flux may contain water, it should be dehydrated periodically with aluminum to minimize the formation of hydrogen when the assemblies are dipped. The aluminum used for dehydrating the bath may conveniently be a loose coil of alloy 1100 or alloy 3003. When hydrogen stops burning at the surface of the bath, dehydration is essentially complete. Initial dehydration should be conducted for 4 to 48 hr, depending on bath size. Insertion of aluminum in the bath before the brazing operation is begun will also remove heavy-metal impurities such as nickel, copper, iron and zinc. The heavy-metal deposit on the aluminum coil is removed by quenching the coil in water, dipping it in nitric acid, and giving it a thorough water rinse. The coil should be dried before being reused.

These operations, as well as the actual brazing, produce a sludge containing oxides from the brazed parts and the brickwork, and insoluble fluoride complexes. After settling, the sludge should be ladled out at periodic intervals with a perforated tool.

Flux will be removed by dragout on the parts being brazed, and must be replaced. When an assembly is dip brazed, there will be approximately 0.5 oz of flux dragout per square foot of flat surface. With heat exchangers having complex and devious passages, this amount may be larger, because of capillary forces holding the flux. For a specific unit, dragout may vary as much as threefold, depending on the melting point and viscosity of the flux.

Before immersion in the flux bath, all moisture must be removed from the assembly and from any fixture used with it. Even a slight amount of mois-

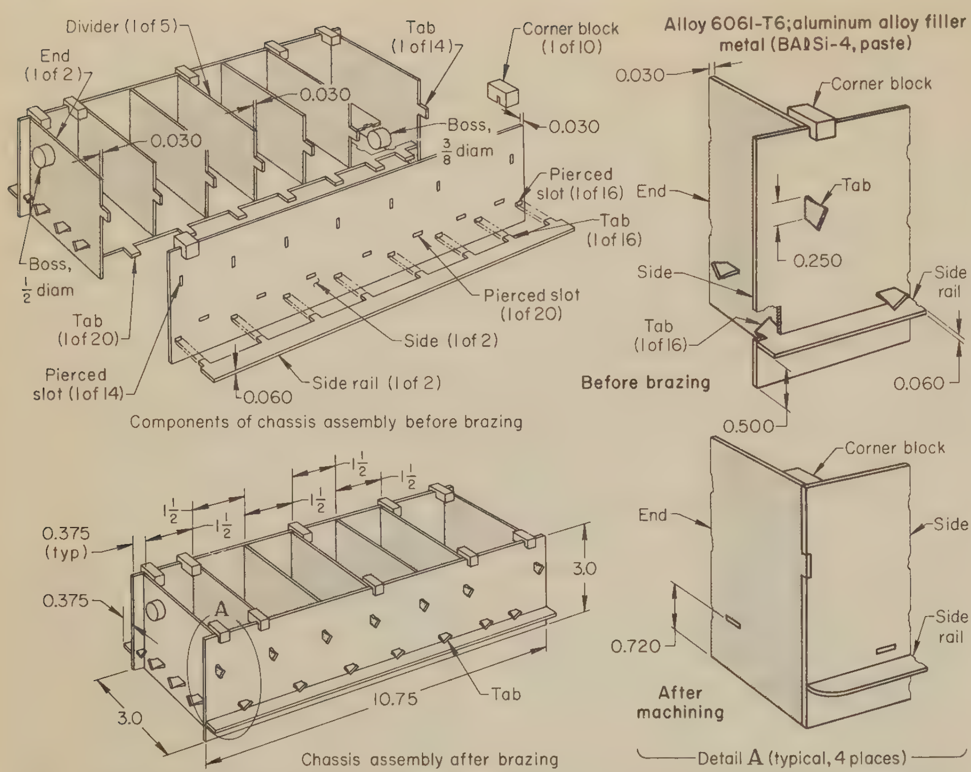


Fig. 9. Dip brazed assembly for an electronic chassis, showing slot-and-tab arrangement for self-jigging (Example 632)

ture can cause spattering in contact with molten flux. Drying by preheating is recommended. The use of preheated assemblies decreases the drop in temperature of the salt bath, shortening brazing time. Large or complex assemblies should be preheated to 1000 to 1050 F, usually in an air-recirculating furnace, at a rate that provides a suitable compromise between distortion from fast heating and diffusion during slow heating. Methods and advantages of preheating are discussed further in the article on Dip Brazing of Steel in Molten Salt, pages 655 to 660.

After being preheated, parts are immediately immersed in the flux bath for the scheduled period. This period will depend somewhat on the mass of the assembly, but immersion is usually only of ½ to 3-min duration. For large assemblies, such as a cryogenic heat exchanger that may weigh more than 1000 lb, immersion time may be as long as 20 min. Time in the bath should be no longer than is required to obtain melting and complete flow of the filler metal. After being preheated, the self-jigged assembly in the following example was dip brazed in only 20 sec.

Example 632. Use of Dip Brazing To Join a Complex Assembly (Fig. 9)

The chassis assembly shown in Fig. 9 was used for airborne electronic equipment. Casting was not a practical method for production of this chassis, because it was a large, thin-wall structure of complex design and the production quantities were small. Resistance spot welding, arc welding and torch brazing were ruled out by the need for a continuous metal surface, close dimensional tolerances and the presence of hidden joints in the design. Dip brazing was selected as the joining method best fulfilling the design requirements.

The dip brazed assembly was made of alloy 6061-T6 as follows. The two ends, two sides, five dividers, two side rails and the bottom were blanked and pierced in a numerically controlled press. The ten corner blocks and the two round bosses were machined from bar stock. Self jigging of the 24 components was achieved by providing the sheet-metal components with slots and mating tabs; the tabs were inserted in the slots, and hand twisted after assembly to hold the components in place. After brazing, the tabs and other extraneous material were machined off (see lower right view in Fig. 9).

This type of assembly allowed brazing with no external fixturing and permitted the use of assembly-line techniques, thus effecting savings of an estimated one fourth to one half of the cost of purchasing the assembly from an outside supplier. Total processing cost (excluding cost of material) was approximately 10¢ per inch of joint, or about $10.00 per assembly.

After burrs larger than 0.005 in. were removed from the sheet-metal components, the chassis was assembled and then cleaned by degreasing followed by immersion in either a caustic bath or a phosphoric acid etching solution. Brazing paste containing BAlSi-4 filler metal was applied to one side of each joint, to ensure against flux entrapment. The assembly was preheated for 20 to 30 min in an electric furnace operating at 1000 F, and then was dipped for 20 sec in a bath of proprietary brazing flux electrically heated to 1400 F.

After brazing, the assembly was cooled to about 500 F by an air blast (to minimize distortion) before being quenched in hot water and washed to remove flux. (The heating for brazing, followed by the air-blast cooling and the hot-water quench, put the 6061 alloy in a condition that yielded a T4 temper after natural aging for several days.)

After the self-jigging tabs and other extraneous metal had been removed by machining, the brazed chassis assembly was inspected visually. Parts were held within 0.015-in. total tolerance of warp over the 10-in. dimension, and angularity of 1° in 3 in. Fillet radii were held within 0.030 to 0.060 in. at junctures of two parts and within 0.030 to 0.090 in. at junctures of three parts. Fluorescent-dye or radiographic inspection was used in special cases. The rejection rate for this chassis was only 2% from all causes.

Furnace Brazing

Brazing in an atmosphere furnace is a high-production process that requires minimum training and skill of operators. Production rates can be considerably higher, and costs can be lower, than for torch brazing. Aircraft hot air ducts are furnace brazed in as little as one twentieth of the time required to torch braze similar parts. Mass-production assemblies, such as refrigerator evaporators, are brazed at about 500 pieces per hour in continuous furnaces.

Equipment. Heating methods for furnace brazing include electrical heating elements, direct combustion tubes and radiant tubes. Direct combustion furnaces are inexpensive, but the furnace gases may cause undesirable metallurgical effects during brazing of the heat treatable alloys — for example, the 6*xxx* series. Furnaces are generally refractory lined, although such linings become saturated with flux components. Heat-resistant steels, which are normally not recommended because of flux attack, are satisfactory for furnace linings if kept clean, and particularly if aluminum coated.

Whatever the type of furnace, the temperature in the brazing zone must be uniform within ±10 F, and preferably within ±5 F. Circulation of atmosphere, preferably with appropriate baffles, is required, to prevent local heat variations and to obtain the maximum rate of temperature rise.

Technique. Flux slurry may be applied to the parts by dipping, brushing or spraying. Tap, distilled or deionized water can serve as a vehicle; tap water should be free of heavy metals, because these can cause subsequent corrosion. Because hydrogen may be evolved when wet flux is heated on aluminum parts, closed assemblies must be vented. Gas generation can be reduced by drying the flux on the part prior to brazing. Mixing the flux with alcohol instead of water will speed the drying, but the explosive fumes from the alcohol must be dissipated.

Ambient air or chemically inert gas is normally used as the furnace atmosphere. A dry atmosphere (dew point of −40 F) consisting of the products of combustion of fuel can sometimes reduce the amount of flux needed. For brazing aluminum to other metals, an inert, dry atmosphere is particularly beneficial.

Continuous furnace brazing requires furnaces divided into several progressive heating zones to improve heating rate and joint quality and to reduce warpage. A furnace cycle of 15 min or less is desirable. In automated operations, the brazing zone usually requires a travel time of 2 to 3 min for assemblies of moderate size. Because the flux loses its activity in about 30 min, aluminum assemblies large enough and heavy enough to require heating times exceeding this limit should not be furnace brazed.

Beyond the heating portion of the furnace, from 1 to 5 min of conveyor travel should be in an unheated zone to allow the filler metal to solidify. Directly following should be an air blast, a hot-water spray (180 to 212 F), or a boiling-water quench, which begins the

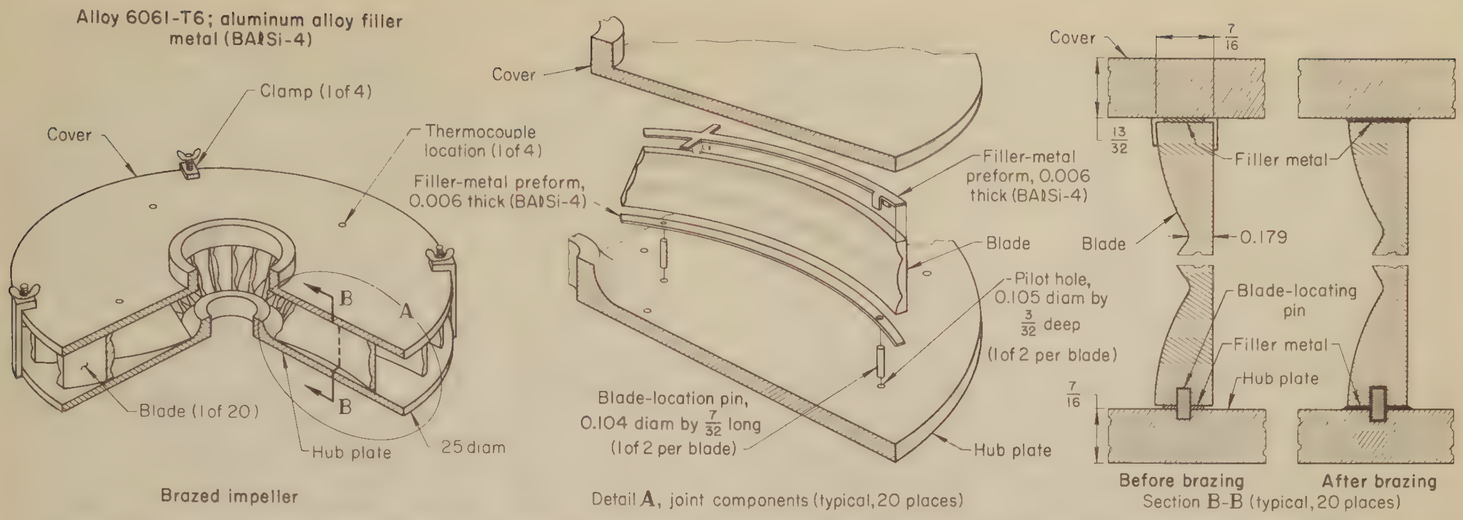


Fig. 10. Furnace brazed impeller assembly, showing the locating pins used to hold the blades in position during brazing (Example 633)

flux-removal process. For the heat treatable alloys, a water quench after brazing will permit improvement in the mechanical properties, especially if the parts are subsequently given an aging treatment.

Batch furnaces are also used for brazing aluminum alloys, as described in the following example.

Example 633. Use of Furnace Brazing To Join an Impeller Assembly (Fig. 10)

Impellers like the one shown in Fig. 10 were used in radial-flow turbo-compressors to increase the recoverable energy content of the gas passing through the compressor. Speeds of various models of impellers ranged from 3000 to 30,000 rpm. More than 80 different sizes of impellers were made. Aluminum was used for impellers that, depending on size and speed, were to run at temperatures up to about 400 F.

The casting of impellers, which was done for some other applications, would have been expensive because of the large investment required for a multiplicity of patterns, the need to make new patterns for design changes and to store the old patterns for replacement orders, the high cost of developing the casting techniques, and expensive inspection requirements.

Brazed impellers were found to be easily manufactured with a large saving in capital cost. The initial capital outlay for producing 80 different sizes of brazed impellers was about 5% of the investment that would have been required for production of the impellers as castings. Design changes were made easily without the need to change equipment. A standard hub plate and cover were used for a number of impeller sizes; only the blade size was changed. Manufacturing cost (exclusive of savings in initial investment) was 1% lower than for casting. Inspection was easier, and the rejection rate of brazed impellers was only one-fourth that of cast impellers. In addition, brazed impellers were salvageable.

Aluminum alloy 6061-T6 plate was selected for the parts of the assembly because of its strength, brazeability and availability. Although brazing destroyed the T6 temper and it was necessary to reheat treat after brazing, the plate was purchased in this temper to avoid possible mixup with other 6061-T6 plate used in the plant, and there was no cost premium for the temper. Blades were cut from a cylinder made by curving the plate on a three-roll former, gas metal-arc welding the longitudinal seam, and stress relieving. The blades were then finish machined to size and shape, and holes for locating pins were drilled on one edge.

The blades, the hub plate (machined and stress relieved), and the cover, together with 0.006-in.-thick BAlSi-4 filler-metal preforms, were cleaned in the following sequence of operations.

1 Immerse in emulsion cleaner at 150 F. The emulsion was a mixture (2 to 3 oz per gallon of water) of alkaline salts combining complex phosphates and sulfates with anionic surface-active agents of the aryl-alkyl sulfonic type.
2 Rinse in cold running water.
3 Immerse in alkaline etching cleaner solution (2 to 3 oz per gallon of water) at 150 to 160 F.
4 Rinse in cold running water.
5 Immerse in nitric acid solution (30 to 40% by weight) at room temperature until all stains or smudges are removed.
6 Rinse in cold running water.
7 Rinse in hot running water.
8 Dry with air blast.

The impeller components and filler-metal preforms were assembled in a clean, air-conditioned room. The hub plate was placed on a rigid baseplate fixture made of type 316 stainless steel. Flux was mixed within 4 hr prior to being used, from 3 parts by volume of a proprietary powder (aluminum fluorides and chlorides) to 1 part of clean water. Aluminum blade-locating pins were inserted in the hub plate and covered with flux. The lower filler-metal preforms were fluxed on both surfaces and put in position over the pins. The blades were fluxed and put in position (located by the pins). The upper filler-metal preform strips were fluxed and placed on the blades.

Tabs were bent down over the blades to hold the filler-metal strips in position. Flux was brushed onto the joint side of the cover. The cover was placed in position over the blades, concentric with the hub plate, and held there by four locating clamps fastened to the cover at 90° intervals and extending down to the bottom of the outside edge of the hub plate.

The cover had been drilled with four ⅛-in.-deep holes on the top surface to accommodate thermocouple beads. For small assemblies, only the holes at the front and back positions during brazing were used. For large assemblies, the holes at the side positions in the furnace also had thermocouple beads peened into them. Care was taken to avoid pickup of foreign metal when making the thermocouple joints and also to avoid contaminating the thermocouple wires with flux.

A box-type furnace, electrically heated on all interior surfaces, was used. The assembly was placed in the furnace, which had been preheated to 1200 F (120 to 130 F above the brazing temperature), and the temperature of the assembly was checked with the thermocouples at regular intervals. When any thermocouple reading was within 50 F of the brazing temperature of 1070 to 1080 F, readings were taken every minute. When the assembly reached brazing temperature, the furnace was opened, and the assembly was removed to cool in air to room temperature. The brazed assembly was washed in hot water to remove flux and then cleaned by the same procedure as used before brazing.

After cleaning, the impeller was solution heat treated, quenched and aged to regain the T6 temper and again was given the same sequence of cleaning operations as before, to remove the slight surface oxidation that formed during heat treatment.

Final inspection included visual examination, dye-penetrant inspection and a hardness check. In addition, the brazed assemblies were inspected for deformation and brazing failure after the impeller was test run 20% over design speed for two minutes in vacuum. Assemblies that showed porosity in a brazed joint were salvaged by recleaning, refluxing, positioning small clips of additional filler metal where needed, and rebrazing. If cracks were found in a joint, the hub plate and cover were salvaged for reuse by cutting apart the assembly. (The used blades were discarded.)

Fluxless Vacuum Brazing

Furnace brazing in a vacuum with the use of no flux offers several advantages. The possibility of flux inclusions is eliminated. Blind cavities, tortuous paths, and small passageways can be designed into the assembly without regard to flux removal or entrapment after brazing. Fluxless brazing also eliminates the cost of flux and its application, the need for cleaning the assembly after brazing, and potential corrosion of equipment and pollution of air and water by flux residues or flux reaction products.

With correct techniques, alloys of the 1*xxx*, 3*xxx*, 5*xxx*, 6*xxx* and 7*xxx* series can be vacuum brazed using X3 and X5 brazing sheets, which are clad with X4003 filler metal. (When additional filler metal is required, X4003 in wire and sheet form also can be introduced.) The joint designs used for brazing with flux can be used for fluxless vacuum brazing.

Equipment. Cold-wall vacuum furnaces with electrical-resistance radiant heaters are recommended for aluminum vacuum brazing. Both batch-type and semicontinuous furnaces are used. The vacuum pumping system should be capable of evacuating a conditioned chamber to a moderate vacuum (about 10^{-5} torr) in 5 min. For most applications, rectangular chambers made of hot rolled steel are suitable. The temperature distribution within the work

Table 5. Typical Conditions for Oxyacetylene and Oxy-Hydrogen Torch Brazing of Aluminum Alloys

Metal thickness, in.	Oxyacetylene brazing: Orifice diameter, in.	Oxygen pressure, psi	Acetylene pressure, psi	Oxy-hydrogen brazing: Orifice diameter, in.	Oxygen pressure, psi	Hydrogen pressure, psi
0.020	0.025	0.5	1	0.035	0.5	1
0.025	0.025	0.5	1	0.045	0.5	1
0.032	0.035	0.5	1	0.055	0.5	1
0.040	0.035	0.5	1	0.065	1	2
0.051	0.045	1	2	0.075	1	2
0.064	0.055	1	2	0.085	1	2
0.081	0.065	1.5	3	0.095	1.5	3
0.102	0.075	1.5	3	0.105	1.5	3
0.125	0.085	2.0	4	0.115	1.5	3

being brazed should be reasonably uniform, ideally within ±5 F. For many applications, wider ranges are used.

Technique. Components are cleaned, usually by vapor degreasing with a common solvent such as perchlorethylene (ordinarily, chemical cleaning is not required), assembled, and clamped in a suitable fixture made of thin stainless steel sheet. The use of dry cotton gloves is recommended for assembling by hand. Heating of the assembly is started simultaneously with pumpdown of batch-type furnaces. Average time for heating to brazing temperature is about 15 min. The assembly is then held at brazing temperature (see optimum brazing ranges, Table 3) for about 1 min. After backfilling the chamber with chemically inert gas, the assembly is removed at approximately 1000 F. Heat treatable alloys can then be quenched; non-heat-treatable alloys are air cooled. The clean, dry brazed assembly is ready for use or further processing as soon as it is cool.

Torch Brazing

Torch brazing is used for either manual or automatic fabrication, and for repair operations. The uses of torch brazing range from rather simple tube-to-tube joints to more complex and mechanized assemblies. Some of the more common commercial applications are tubular joints in refrigerator coils, miter joints in extruded window frames, and joints between electric heating elements and structures.

Equipment. Oxyacetylene, oxy-hydrogen and oxy-natural gas are employed commercially for torch brazing. It is possible also to use gasoline blowtorches, and all types of gas burners.

Torch brazing is similar to gas welding, in that the heat to effect the joint is applied locally. The torch-tip sizes used are also similar to those for gas welding. The choice of tip size and gas pressures depends on the thickness of the parts and should be determined by trial, using the values in Table 5 as starting points.

With the generally employed fillers, BAlSi-3 (alloy 4145) and BAlSi-4 (alloy 4047), close temperature control is needed, especially for torch brazing of alloys having low solidus (wrought alloys 5052, 6053, 6061 and 7005, and the casting alloys listed in Table 1). Since aluminum alloys show no color when hot, even melting without a color change, it is necessary to have some means for determining when the parts are reaching brazing temperature. The flux used should be one that melts at a slightly lower temperature than the filler metal and thus serves as a temperature indicator. Aligning jigs should be insulated to avoid excessive heat conduction.

Technique. After the components of an assembly to be torch brazed have been suitably cleaned, the joint areas and the filler metal are painted with a slurry of brazing flux, and the components assembled and (if required) jigged. The assembly is then brazed by directing a soft, slightly reducing flame over the entire joint area. The filler metal can be preplaced, or it can be face fed (flowed into the joint when touched against the heated work). The brazed joint should have a smooth fillet, usually requiring little or no finishing. All flux should be removed.

Specialized Brazing Processes

The various processes described in this section are not currently in wide use. For some of these processes, the basic art, knowledge and materials are available, but the applications to date are meager. For others, the technology is not fully developed.

Modifications of Dip Brazing. In one modification of dip brazing, mixtures of filler-metal powder and one of the active components of the flux, such as a fluoride, are applied to the areas to be brazed and are dried, and then the assembly is dipped into a less-active molten flux vehicle.

Another modification is useful when, because of joint design, it is desirable to supply filler metal from a molten bath. This is done in either of two ways: (*a*) assemblies coated with flux (by spraying or dipping) and thoroughly dried are placed into the molten filler metal; or (*b*) the assembly is dipped into a molten flux bath and then dipped into the molten filler metal. In either method, the molten filler metal flows into the capillary spaces at the joints to effect a braze.

Resistance brazing of aluminum alloys most often involves joining of small parts: making connections in electric motor windings is a typical application. Usually, the work is clamped for heating between two carbon blocks held in a tong arrangement. For some jobs, it is clamped in a resistance welding machine.

Alloy Brazing. This fluxless process achieves a braze by first heating the joint area with an interposed shim to form a liquid phase, then extruding this liquid along with surface oxides from the joint cross section. Because of rate of alloying, fluidity, melting temperature, and availability as foil, the preferred shim material is copper. The extreme brittleness of the aluminum-copper intermetallic compounds is no deterrent, because the compounds are entirely displaced by extrusion.

Many types of heating are used for alloy brazing; resistance heating is commonest. Clamping pressure between the carbon blocks is generally 1200 to 2000 psi, based on the overlap area. Current densities of 2500 to 4000 amp per square inch with an operating potential of 9 to 13 volts are satisfactory.

This process is used in the electrical industry, because the electrical conductivity of the brazed joints is essentially the same as the parent aluminum conductor, and the process is low in cost. In addition to simple overlap and butt joints, multiple-ply overlap, thin-to-thick, and round-to-flat joints have been brazed. The simple, inexpensive, fluxless features also make this process attractive for brazing narrow sheet and plate members, butt joining round and square aluminum rod, and sealing the ends of thin-wall tubing. Alloys such as EC, 1060, 1100 and 3003, with solidus temperatures considerably above 1018 F (aluminum-copper eutectic temperature), are the most readily brazed. The 5*xxx* and 6*xxx* alloys with lower solidus temperatures can be brazed if close temperature control is provided.

Motion brazing includes both vibration brazing and flow brazing. As might be expected, vibration of low or ultrasonic frequency has a pronounced beneficial effect in brazing aluminum, particularly when brazing sheet is used. Brazed joints can be made with brazing-sheet parts in the absence of flux and in air. The brazing-sheet surfaces are held together at a temperature preferably above the liquidus of the brazing alloy. A relative movement between the brazing sheets displaces the oxide film on the semiliquid contact surfaces.

In flow brazing, simple joints can be brazed between brazing sheets or even plain aluminum parts. The part to be brazed or the molten filler metal is moved rapidly with respect to the other, causing a mechanical removal of oxide film and the mating of liquid-liquid or solid-liquid interfaces. For simple shapes, this can be done in air; for more difficult shapes, in an inert gas. No flux is used. Vibration is helpful. The total time must be short.

The motion brazing concept has certain obvious limitations. Parts are restricted to rather elementary structures because of the requirements of directional vibration, rate and type of motion, supply of premelted filler alloy to the joint, shape of part, precleaning, and other complicating factors.

Brazing to Other Metals

Aluminum can be brazed to many other metals. In specific applications, painting or other suitable coating may be required after brazing, to minimize subsequent galvanic corrosion of the joint area. Stresses from nonuniform expansion must also be considered.

Aluminum to Ferrous Alloys. Steel should be protected from oxidation during preheating and brazing to aluminum. In dip brazing, oxidation can be prevented by dipping unheated

parts into molten flux, but this procedure has limited application because it is likely to cause warping and misalignment of the components.

Plated or coated steel can be brazed to aluminum more readily than can bare steel. Copper, nickel or zinc electroplates and aluminum, silver, tin or hot dip zinc coatings are used to promote wetting of the steel and to minimize formation of brittle aluminum-iron constituents, thus producing a more ductile joint.

The furnace brazing of plated steel liners or sleeves in aluminum alloy cylinder blocks, as well as steel valve seats in aluminum alloy cylinder heads, has been done experimentally.

Aluminum-coated steels can be torch brazed readily to aluminum, using aluminum filler metals and fluxes. The procedure is the same as in brazing aluminum to aluminum except that preheating should be rapid and brazing time must be minimized, in order to avoid the formation of brittle aluminum-iron phases at the interface. Tube-to-tube joints, with a nominal clearance of about 0.010 in., and laps varying from 0.50 to 2.50 in., have shown shear strengths of 10,000 to 15,000 psi.

In certain complex applications, a multiple-step joining procedure must be employed to permit flux removal. For instance, a section of steel tube was hot dip coated with aluminum at one end, and the aluminum-coated end was dip brazed to a section of aluminum tube. After thoroughly cleaning the brazed subassembly to remove residual brazing flux, the aluminum tube portion was welded to an aluminum container that had been furnace brazed and cleaned in separate operations. The completed assembly was vacuum tight.

Aluminum to Copper. It is difficult to braze aluminum to copper, because of the low melting temperature (1018 F) of the aluminum-copper eutectic and its extreme brittleness. By heating and cooling rapidly, however, reasonably ductile joints are made for applications such as copper inserts in aluminum castings. The usual filler metals and fluxes for brazing aluminum to aluminum can be used, or the silver alloy filler metals BAg-1 and BAg-1a can be used if heating and cooling are rapid (to minimize diffusion). Pretinning the copper surfaces with solder or silver alloy filler metal improves wetting and permits shorter time at brazing temperature. A more practical way to braze aluminum to copper is to braze one end of a short length of aluminum-coated steel tube to the aluminum, and then silver braze the other end of the tube to the copper.

Aluminum to Other Nonferrous Metals. Aluminum-silicon filler metals are unsuitable for brazing aluminum to uncoated titanium because of the formation of brittle intermetallic compounds, but titanium can be hot dip coated with aluminum, after which it can be brazed to aluminum with the usual aluminum filler metals.

Under correct conditions, nickel and nickel alloys are no more difficult to braze to aluminum than are ferrous alloys. They can be brazed directly or precoated with aluminum. Although Monel alloys can be wetted directly, brazed joints are likely to be brittle, and Monel alloys are thus preferably precoated with aluminum.

Beryllium can be wetted directly by aluminum brazing alloys. Magnesium alloys can be brazed to aluminum, but the brazed joints have limited usefulness because of the extremely brittle aluminum-magnesium phases that form at the interface.

Table 6. Solutions for Removing Brazing Flux From Aluminum Parts

Type of solution	Concentration: Amount	Concentration: Component(a)	Operating temperature	Procedure(b)
Nitric acid	5 gal 34 gal	58 to 62% HNO_3 Water	Room	Immerse for 10-20 min; rinse in hot or cold water(c)
Nitric-hydrofluoric acid	4 gal 1 qt 36 gal	58 to 62% HNO_3 48% HF (1.15 sp gr) Water	Room	Immerse for 10-15 min; rinse in cold water, rinse in hot water; dry(d)
Hydrofluoric acid	10 pt 40 gal	48% HF Water	Room	Immerse for 5-10 min; rinse in cold water; dip in nitric acid solution shown at top of table; rinse in hot or cold water(d)
Phosphoric acid – chromium trioxide	1½ gal 7¼ lb 40 gal	85% H_3PO_4 CrO_3 Water	180 F	Immerse for 10-15 min; rinse in hot or cold water(e)
Nitric acid – sodium dichromate	4½ gal 32 lb 36 gal	58 to 62% HNO_3 $Na_2Cr_2O_7 \cdot 2H_2O$ Water	140 F	Immerse for 5-30 min; rinse in hot water(f)

(a) All compositions in weight per cent. (b) Before using any of the above solutions, it is recommended that the assembly first be immersed in boiling water to remove the major portion of the flux. (c) Flux contamination in acid should not exceed 5 grams per liter of chloride expressed as sodium chloride. Solution is not recommended for use on base metals less than 0.020 in. thick.

(d) Flux contamination in acid should not exceed 3 grams per liter of chloride expressed as hydrochloric acid. Solution is aggressive, and not recommended for base metals less than 0.020 in. thick. (e) Tolerance for flux contamination is in excess of 100 grams per liter, and permissible limit will probably be governed by cleaning ability. If large pockets of flux are present, solution will promote intergranular attack at the pocket. Recommended for final cleaning of thin-gage parts, when most of the flux can be removed easily in water. (f) Exceptionally high flux tolerance. Recommended for cleaning thin-gage assemblies, if adequacy of water cleaning is doubtful. License required.

Flux Removal

Fluxes used in brazing aluminum alloys can cause corrosion if allowed to remain on the parts. It is therefore essential to clean joints after brazing. A thorough water rinse followed by a chemical treatment is the most effective means of complete flux removal.

As much flux as possible should be removed by immersing the parts in an overflowing bath of boiling water just after the filler metal has solidified. If such a quench produces distortion, the parts should be allowed to cool in air before immersion, to decrease the thermal shock. When both sides of a brazed joint are accessible, scrubbing with a fiber brush in boiling water will remove most of the flux. For parts too large for water baths, the joints should be scrubbed with hot water and rinsed with cold water. A pressure spray washer may be the best first step. A steam jet is also effective in opening passages plugged by flux.

Any of several acid solutions (Table 6) will remove any flux remaining after washing. The choice depends largely on the thickness of the brazed parts, accessibility of fluxed areas and the adequacy of flux removal in the initial water treatment. A pitting or intergranular type of attack on parts can result as chlorides from the flux build up in the acid solution. Some solutions have a greater tolerance for these chlorides than others before parts are attacked. The degree of flux contamination tolerable for the five typical flux-removal solutions listed in Table 6 are given in the footnotes of the table.

The two chromium-containing solutions in Table 6 have the greater tolerance for chlorides and are preferred for thin-wall assemblies. In areas where disposal of chromates presents a problem, the nitric acid solution can be used if inhibitors such as 1% thiourea or triethanolamine salt of sulfolaurylalkylbenzoate are added. As a corrosion inhibitor, about 0.5% sodium or potassium dichromate is sometimes added to the final rinse water.

Agitation and turbulence improve the efficiency of any flux-removal treatment. Ultrasonic cleaning is effective for cleaning inaccessible areas, decreases the immersion time and reduces the possibility of attack on the aluminum.

Checking for complete flux removal should be a routine inspection procedure. To detect the presence of flux, a few drops of distilled water are put on the surface to be tested and left there for a few seconds. The water is then picked off with an eyedropper and placed in an acidified solution of 5% silver nitrate. If the solution stays clear, the metal is clean. If a white precipitate clouds the solution, flux was present on the surface. Flux-removal procedures must then be repeated until the brazed assembly tests clean. Complete removal of the flux is essential, because it is corrosive to aluminum in the presence of moisture.

Postbraze Heat Treatment

Brazing temperatures exceed the solution heat treatment temperatures used for aluminum alloys, and heat treatable aluminum alloys can attain full strength by aging after being quenched from the brazing temperature. After brazing of alloy 7005, a normal air quench for small parts of 5 F per second, or even a cooling rate as slow as 1 F per second, is adequate for precipitation hardening to occur at room temperature. Except as dictated by distortion problems, postbraze quenching and aging treatments are the same as for the base alloy. Typical treatment for artificially aging a heat

treatable alloy brazed assembly is 16 to 20 hr at 320 F, or 6 to 10 hr at 350 F.

Finishing

Because of the smooth, uniform fillets resulting from the brazing operation, little if any mechanical treatment is required before final finishing. If flux has been completely removed (or if fluxless brazing has been used), all chemical and electrochemical finishing treatments are effective when the brazed structures are aluminum throughout. Because of the high silicon content of the filler-metal fillets, any treatment that thickens the oxide or preferentially etches aluminum, leaving a residue of silicon, may cause the fillets to be a darker color than the remainder of the product.

Brazing fluxes containing chlorides of zinc or other heavy metals will deposit that metal on the surface of aluminum parts. These fluxes, as well as fluxes that cause severe etching of aluminum, should be avoided for highest quality in chemical finishing.

Mechanical Properties

At least a part of the base metal is heated above its annealing temperature during the brazing cycle. Torch brazing may anneal only a small region near the joint, whereas dip or furnace brazing anneals the entire assembly. Unless the completed part is quenched and aged, heat treated, or cold worked, the metal that was heated will have mechanical properties typical of the annealed alloy.

When the alloy is heat treatable, improved strength can be imparted by quenching directly from the brazing furnace or dip pot, then artificially or naturally aging according to regular procedures for the alloy involved. Another alternative is solution heat treating and aging as separate operations after brazing. Heat treating is not always possible, because the rapid quenching required for most heat treatable alloys can cause distortion. Alloy 7005 will age harden at room temperature to T6 properties after normal air cooling (1 to 2 F per sec) from brazing temperature. Table 7 lists typical properties of alloy 7005 air cooled from brazing temperature.

Table 7. Tensile Properties of 0.063-In.-Thick Alloy 7005 Heated as in Brazing (a)

Room-temperature aging treatment	Tensile strength, psi	Yield strength, psi	Elongation in 2 in., %
None	28,000	12,000	26
3 days	42,000	21,000	22
1 week	45,000	24,000	22
1 month	49,000	27,000	21
3 months	52,000	30,000	21
6 months	54,000	32,000	21
T63(b)	52,000	44,000	13

(a) Heated 10 min at 1090 F, air cooled, aged as designated. (b) Artificially aged (after solution heat treatment).

Resistance to Corrosion

The aluminum alloys best suited for brazing are also among those most resistant to corrosion. Corrosion resistance of aluminum alloys generally is unimpaired by brazing if a fluxless brazing process is used or if flux is completely removed after brazing. If flux removal is inadequate, the presence of moisture can lead to interdendritic attack on the filler metal at joint faces and to intergranular attack on the base metal.

When two aluminum alloys are brazed together, exposure to salt water or some other electrolyte may result in attack on the more anodic alloy. This condition is aggravated if the anodic part is relatively small compared with the other piece. It helps, therefore, to have the anodic aluminum alloy the larger of the two members.

Torch brazed alclad 3003 and alclad 3004 show excellent resistance to corrosion. Furnace or dip brazing, however, causes a certain amount of diffusion of the clad surface, which limits application of these methods with conventional alclad products. A brazing sheet with filler metal on one side and alclad with a special alloy on the other (see Fig. 2d) performs well in furnace or dip brazing.

Commercial filler metals of the aluminum-silicon type have high resistance to corrosion, comparable to that of the base metals usually brazed. Filler metals containing substantial amounts of copper or zinc are less resistant to corrosion, but they are usually adequate, except for service in severe environments.

Joints brazed with aluminum-silicon filler metals — BAlSi-2 (alloy 4343), BAlSi-4 (alloy 4047) and BAlSi-5 (alloy 4045) — all show a potential of −0.82 volt with respect to a 0.1*N* calomel reference electrode in an aqueous solution of 53 grams-per-liter of sodium chloride and 3 grams-per-liter of hydrogen peroxide. This potential is barely cathodic to the commonly brazed base metals, for which the value is −0.83 volt for 1100, 3003, 6061 and 6063. Therefore, there is little electrolytic action in assemblies of these base metals brazed with the usual filler metals.

The potential of joints brazed with filler metal BAlSi-3 (alloy 4145), which contains copper in addition to aluminum and silicon, depends on the cooling rate after brazing. For slow cooling, these joints have about the same potential as joints brazed with the aluminum-silicon filler metals (−0.82 volt). If the cooling is rapid enough to retain a substantial amount of copper in solid solution, the potential will be lower; a potential of −0.73 volt has been found for T-joints in 0.064-in. sheet brazed with BAlSi-3 filler metal and rapidly cooled.

Although considerable undissolved silicon-containing constituent is evident in brazed joints, it polarizes strongly (except in acid chloride environments) and has little influence on the potential of the brazed joint and its corrosion resistance.

Table 8 shows the results of long-time exposure in a highly corrosive environment of various sheet alloys that were furnace brazed with filler metal BAlSi-3 (alloy 4145). The good performance can be considered typical of a variety of brazing combinations.

Table 8. Results of Microscopic Examination of Furnace Brazed Specimens Exposed Two Years to 3.5% Sodium Chloride Intermittent Spray (a)

Sheet alloy	Filler metal(b)	Sheet (base metal): Type of attack(c)	Sheet: Depth of attack, in.: Maximum	Sheet: Depth of attack, in.: Average	Joint (filler metal): Type of attack(c)	Joint: Depth of attack, in.: Maximum	Joint: Depth of attack, in.: Average
3003	4145	P	0.0098	0.0022	P	0.0014	0.0011
5052	4145	P	0.0182	0.0042	P	0.0042	0.0014
6053	4145	P + I	0.0126	0.0028	P	0.0012	0.0008
6061	4145	P + SI	0.0126	0.0033	P	0.0042	0.0014

(a) Specimens were small inverted T-joints of 0.064-in. sheet. (b) Filler metal 4145 corresponds to BAlSi-3. (c) P = pitting attack; I = intergranular attack; SI = slight intergranular attack.

Safety

Many of the safety considerations discussed in the articles on brazing processes (pages 593 to 660) are applicable to the brazing of aluminum alloys by the same processes. The principal hazard in brazing aluminum alloys that is not present in brazing steel or copper alloys arises from the use of molten fluorine-containing fluxes in dip brazing. Toxic effects may be produced by the inhalation of fumes from the fluorine compounds, and exhaust facilities are required for dip brazing. Furnace brazing with fluorine-bearing fluxes requires regular exhaust of the fumes generated, to prevent attack on exposed metals; the air changes necessary for this reason are also adequate from the standpoint of health protection.

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Brazing of Copper and Copper Alloys

*By the ASM Committee on Welding and Brazing of Copper and Copper Alloys**

MOST commercial coppers and copper alloys can be brazed satisfactorily, using one or more of the conventional brazing processes (furnace, torch, induction, resistance, and dip brazing).

Brazeability

The brazeability of coppers and copper alloys is generally rated from good to excellent. With some of the brazeable alloys, however, specific difficulties may be encountered. For example, some lead-containing alloys can form a dross that interferes with wetting, and several tin-containing alloys, if not stress relieved before brazing, may crack when subjected to rapid localized heating. The brazing characteristics of the coppers and the principal groups of copper alloys are considered in the following paragraphs. Nominal compositions of commercial coppers and copper alloys are tabulated on pages 338 and 476 in this volume.

Coppers. Included in this group are electrolytic tough pitch (ETP), phosphorus-deoxidized (DLP and DHP), and oxygen-free (OF) coppers, together with coppers containing not more than about 1% of an additive element, such as silver (STP), zirconium, chromium, lead, selenium, tellurium or sulfur.

Electrolytic tough pitch copper is subject to embrittlement when heated in a hydrogen-containing atmosphere. The rate of diffusion of hydrogen in heated copper is high, and at temperatures above 900 F even relatively small amounts of hydrogen result in embrittlement and internal cracking due to the reduction of copper oxide by hydrogen and the formation of water vapor within the solid metal. Consequently, although electrolytic tough pitch copper is generally rated as having good to excellent brazeability, it should not be brazed in a furnace that contains hydrogen or a hydrogen-containing prepared atmosphere such as dissociated ammonia, or in an exothermic-base or endothermic-base atmosphere. Heating by open flame or by torch also may result in hydrogen diffusion and embrittlement.

Phosphorus-deoxidized and oxygen-free coppers can be brazed in hydrogen-containing atmospheres without risk of embrittlement and, provided the self-fluxing copper-phosphorus or copper-silver-phosphorus filler metals (BCuP series) are used, can be brazed without flux. The use of flux is normally required, however, when the silver alloy filler metals that contain additives such as zinc, cadmium or lithium (BAg series) are used to braze these coppers or to braze these coppers to copper alloys or other metals.

*For committee list, see page 337. More than half of the examples presented in this article were contributed by members of other Metals Handbook welding and brazing committees.

The coppers that contain small additions of silver, lead, tellurium, selenium or sulfur (generally no more than 1%) are readily brazed with the self-fluxing BCuP filler metals, but wetting action is improved when a flux is used and when a sliding motion between components is provided while the filler metal is molten. Coppers that contain beryllium, chromium or zirconium are precipitation hardenable; brazing these coppers in the aged condition impairs their mechanical properties. However, when it is possible to combine brazing with solution heat treatment, properties can be at least partly restored by a subsequent aging treatment.

Beryllium copper can be brazed and solution heat treated by heating to 1450 F, followed by rapid quenching. Subsequent aging at about 600 F will develop maximum hardness. When the sections to be brazed are thin and can be cooled very rapidly, it is often possible to braze solution heat treated beryllium copper in the temperature range of 1150 to 1200 F, quench rapidly, and age to a hardness that approaches the maximum obtainable. To ensure proper wetting, the joint surfaces of beryllium copper parts should be freshly machined or mechanically abraded before being brazed; to remove the beryllium oxide from joint surfaces, a flux with a high fluoride content should be used.

When chromium and zirconium coppers are brazed at a temperature within the solution treatment range (1800 F, for example), brazing and solution treatment can be combined, provided the parts can be cooled rapidly from the brazing temperature. Brazed parts can then be aged in a subsequent operation to develop desired mechanical properties and electrical conductivity.

Red brasses (copper-zinc alloys that contain up to 20% zinc) are readily brazed with a variety of filler metals. Flux is normally required for best results.

Yellow brasses (copper-zinc alloys that contain 25 to 40% zinc) are readily brazed, but low-melting filler metals should be used, to avoid dezincification of the base metal. Yellow brasses are susceptible to stress-corrosion cracking, particularly in the presence of ammonium compounds. Therefore, they should never be brazed in ammonia-containing atmospheres.

Leaded Brasses. When added to red brass or yellow brass, lead forms a dross on heating that can seriously impair wetting and the flow of filler metal. Consequently, in brazing of leaded brasses, the use of a flux is mandatory, to prevent dross formation in the joint area.

The susceptibility of leaded brasses to hot cracking varies directly with lead content. Therefore, these alloys must be essentially free of residual stress prior to brazing. Heating to the brazing temperature should be slow and uniform, to minimize thermal stressing. Brazing results are poor at a lead content of 3% and become worse as the lead content is increased, because of grain-boundary effects and the brittleness of phases formed in the joint by lead and the filler metal. Alloys containing more than 5% lead should never be brazed.

Tin-containing brasses, which include admiralty brass, naval brass and leaded naval brass, contain up to 1% tin and may contain other alloying elements such as lead, manganese, arsenic, nickel and aluminum. Except for the aluminum-containing alloys, these brasses are readily brazed; they have greater resistance to thermal shock and are less susceptible to hot cracking than the high-lead brasses. For proper wetting, the brasses that contain aluminum require a special flux, such as type 4.

Phosphor Bronzes. These copper-tin alloys contain small amounts of phosphorus, up to about 0.25%, added as a deoxidizer. Although susceptible to hot cracking in the cold worked condition, alloys in this group have good brazeability and are adaptable to brazing with any of the common filler metals that have melting temperatures lower than that of the base metal. The use of a flux is generally preferred. To avoid cracking, parts made from phosphor bronzes should be stress relieved at approximately 375 F before brazing.

Silicon bronzes, which contain up to about 3.25% silicon and are in a highly stressed condition, are susceptible to hot shortness and stress cracking by molten filler metal. To avoid cracking, the alloys should be stress relieved at about 475 F prior to brazing. For best brazing results, joint surfaces should be freshly machined or mechanically cleaned. Silicon bronzes containing aluminum require the use of type 4 flux (see page 686 and Table 2).

Aluminum Bronzes. Because of their aluminum content, which results in the formation of aluminum oxide on the surface, aluminum bronzes are generally considered difficult to braze. However, alloys containing 8% aluminum or less are brazeable, provided type 4 flux is used to dissolve the aluminum oxide. The oxide, which inhibits the flow of filler metal, cannot be reduced in dry hydrogen. Use of the low-melting high-silver filler metals is recommended for these bronzes.

Copper nickels, which may contain from about 10 to 40% nickel, are susceptible both to hot cracking and to stress cracking by molten filler metal. The silver alloy filler metals (BAg series) are preferred for brazing these alloys. In general, the use of filler metals containing phosphorus should be avoided, because the copper nickels are susceptible to the formation of brittle nickel phosphides at the interface, which lowers joint ductility.

Nickel silvers (brasses that contain up to about 20% nickel but that do not contain silver) are highly susceptible to hot cracking and should be stress relieved at about 475 F before being brazed. They have low thermal conductivity and should be heated and cooled slowly and uniformly.

Brazing Dissimilar Alloys. Most of the alloys belonging to any one of the above groups can be brazed to an alloy of another group. However, to achieve compatibility, some compromise may be required in the selection of brazing temperature, filler metal and flux. For example, if a component made of copper is to be brazed to a component made of aluminum bronze, the brazing temperature should be predicated on the lower melting temperature of the bronze rather than on the higher melting temperature of the copper, and a suitable flux should be selected to accommodate the bronze, even though the copper could be brazed satisfactorily without a flux, using a self-fluxing filler metal of the BCuP series.

It is not uncommon for three or more different copper alloys to be brazed together in a single assembly (see Example 636).

Filler Metals

Table 1 presents the nominal compositions, solidus and liquidus temperatures, and electrical conductivities of some filler metals commonly used in brazing of copper and copper alloys, and the joint clearance used with each. The filler metals listed in Table 1 represent four series: copper-zinc (RBCuZn) alloys, copper-phosphorus and copper-silver-phosphorus (BCuP) alloys, silver (BAg) alloys, and gold (BAu) alloys. Omitted from Table 1 are the copper (BCu) filler metals, which, because of their high liquidus temperature (1980 F), are restricted to use with the copper-nickel alloys only. Of the filler metals listed in Table 1, the BCuP and BAg alloys are by far the most widely used in brazing copper and its alloys.

Copper-Zinc (RBCuZn) Filler Metals. Because of their high liquidus temperatures, their limited corrosion resistance, and their sensitivity to overheating, the copper-zinc filler metals are seldom used in brazing copper and copper alloys. Overheating causes the zinc to vaporize and form voids in the joint. In applications where corrosion resistance is not of importance, these filler metals can be used for joining copper, copper nickel, silicon bronze, and phosphor bronze. They are sometimes used in joining copper to steel, stainless steel and nickel alloys. In general, these filler metals require the use of a flux.

Copper-Phosphorus and Copper-Phosphorus-Silver (BCuP) Filler Metals. The BCuP alloys are self-fluxing when used for brazing unalloyed coppers, but the use of a flux is generally recommended when these filler metals are employed in brazing the special coppers and copper alloys. The BCuP filler metals are not used in brazing beryllium copper, because the resulting deposit in the joint is highly porous; in general, they are not suitable for use in brazing copper-nickel alloys containing more than 30% nickel. The BCuP filler metals have good corrosion resistance, but they are severely attacked in sulfur-bearing atmospheres at elevated temperature. Among the advantages of these filler metals are their relatively low cost.

Silver Alloy (BAg) Filler Metals. The silver alloy filler metals listed in Table 1 are suitable for use with all brazeable coppers and copper alloys and most dissimilar-alloy combinations. The lower brazing temperatures indicated in Table 1 for some of the silver alloy filler metals make them particularly well-suited for brazing copper alloys with an appreciable zinc content, such as the yellow brasses, which are subject to dezincification. The corrosion resistance of silver alloy filler metals ranges from good to excellent, although the cadmium-containing silver alloys are avoided when brazing equipment for the dairy, food, and pharmaceutical industries, because of the high toxicity of cadmium. The principal disadvantage of silver alloy filler metals is high cost, but this disadvantage can be largely offset by correct joint design. Flux is generally required for all but the lithium-containing filler metals (BAg-8a and BAg-19), which are self-fluxing in dry, nonoxidizing protective atmospheres by virtue of the ability of lithium to reduce refractory oxides on the base-metal surfaces at brazing temperature.

Gold alloy (BAu) filler metals, such as BAu-4 in Table 1, are high-cost compositions that are generally restricted to applications requiring exceptional corrosion resistance and to highly specialized applications such as joining vacuum-tube components that are hermetically sealed, where the low vapor pressure of gold is advantageous. The high liquidus temperatures of gold alloy filler metals further limit their use to brazing coppers and a few high-melting copper-nickel alloys.

Brazing Fluxes

The four types of fluxes used in brazing of coppers and copper alloys are listed in Table 2. All are marketed as proprietary compositions; there are no standard composition ranges.

Type 3A is a general-purpose, low-temperature flux suitable for use with all copper and copper alloy base metals except those containing substantial amounts of aluminum. The filler metals that are compatible with this flux include most of the copper-phosphorus alloys (with the exception of BCuP-1) and most of the silver alloys (including all those with liquidus temperatures below 1600 F).

Type 3B flux is a modification of type 3A for use at higher temperatures. The active temperature range of type 3B flux is 1350 to 2100 F. This flux can be used for brazing with any of the filler metals listed in Table 1, provided the brazing temperature is above 1350 F.

Type 4 flux is specifically formulated for brazing the aluminum-bearing copper alloys, and has the same working-temperature range as type 3A flux — 1050 to 1600 F. This flux is generally used with the silver alloy filler metals.

Type 5 flux, which has a working-temperature range of 1400 to 2200 F, is most commonly used with the copper-zinc filler metals. It is less active than type 3B flux, but it remains active longer (as required by the longer heating cycles used to braze heavy components), and costs less.

Joint Clearance

Joint clearance is a principal factor in determining the mechanical strength of brazed joints. It is also a factor in eliminating harmful voids in the joint area and in establishing the capillary force required to fill the joint.

Typical diametral joint clearances for use with the filler metals commonly employed in joining copper and copper alloys are given in Table 1. These are clearances at room temperature and are applicable to brazing components of about the same mass made from the same copper or copper alloy. Adjustments may be required for brazing dissimilar metals to compensate for different coefficients of thermal expansion.

Selection of Brazing Process

Often the size and shape of an assembly will suggest a preferred brazing process to the exclusion of other proc-

Table 1. Nominal Compositions, Solidus and Liquidus Temperatures, and Electrical Conductivities of Some Filler Metals Commonly Used in Brazing of Copper and Copper Alloys, and Typical Joint Clearances Used With These Filler Metals

Filler metal, AWS	Nominal composition, %							Solidus temperature, F	Liquidus temperature, F	Conductivity, % IACS(a)	Typical diametral joint clearance (at room temperature), in.
	Ag	Cu	P	Zn	Cd	Ni	Other				
RBCuZn-A	...	59.25	...	40	...	...	0.75 Sn	1630	1650	26	0.002 to 0.005
RBCuZn-D	...	48	...	42	...	10	...	1690	1715	...	...
BCuP-1	...	95	5	...	...	...	...	1310	1650	...	0.002 to 0.005
BCuP-2	...	92.75	7.25	...	...	...	...	1310	1460	...	0.001 to 0.003
BCuP-4	6	86.75	7.25	...	...	...	...	1190	1335	...	0.001 to 0.003
BCuP-5	15	80	5	...	...	...	...	1190	1475	10	0.001 to 0.005
BAg-1	45	15	...	16	24	...	...	1125	1145	28	0.002 to 0.005
BAg-1a	50	15.5	...	16.5	18	...	...	1160	1175	24	0.002 to 0.005
BAg-2	35	26	...	21	18	...	...	1125	1295	29	0.002 to 0.005
BAg-3	50	15.5	...	15.5	16	3	...	1170	1270	18	0.002 to 0.005
BAg-5	45	30	...	25	...	...	...	1250	1370	19	0.002 to 0.005
(b)	75	22	...	3	...	...	...	...	1365	...	0.002 to 0.005
BAg-8a	72	27.8	...	...	...	...	0.2 Li	1410	1410	89(c)	0.002 to 0.005
BAg-19	92.5	7.3	...	...	...	...	0.2 Li	1435	1635	88(c)	0.002 to 0.005
BAu-4	...	...	...	...	...	18	82 Au	1740	1740	6	0.002 to 0.005

(a) Ratio of electrical resistivity of International Annealed Copper Standard at 68 F (20 C) to the resistivity of the material at 68 F (20 C), expressed as a percentage and calculated on a volume basis. (b) Special filler metal used in brazing nickel silver knife handles (see Example 637). (c) Conductivity of filler metal after volatilization of lithium in brazing.

esses. When two or more brazing processes have approximately equal suitability for brazing a given assembly, the quantity of assemblies to be brazed, because of its direct bearing on cost, is likely to be the deciding factor in process selection.

Comparative production rates and labor costs for brazing each of three different assemblies by different brazing processes are given in Table 3. Additional data are presented in the sections of this article that deal with the various brazing processes.

The five sections that comprise the remainder of this article discuss aspects of furnace brazing, torch brazing, induction brazing, resistance brazing, and dip brazing that are specific to the application of the five processes to copper and copper alloys. These sections also present 28 examples of production practice illustrating the use of the processes.

For detailed discussion of equipment and operating conditions that may be generally applicable to the use of the five processes in brazing any metal, the reader is referred to the five articles on pages 593 to 660 in this volume, which deal individually with the different brazing processes.

Furnace Brazing

Furnace brazing is a mass-production process. Its primary advantage is that it can be used to process a large number of assemblies on a batch or continuous basis at low unit cost. Other advantages of furnace brazing are that it can be used to braze a number of joints on the same assembly simultaneously, or to braze a variety of different assemblies simultaneously, and that it provides an enclosed container for atmospheres that can protect assemblies against surface oxidation and other undesirable effects encountered when heating in air.

In all furnace brazing applications, the filler metal must be preplaced before the assembly enters the furnace, and retained in position until brazing and solidification are completed.

Advantages of furnace brazing that are more specifically applicable to the joining of copper and copper alloys relate to the furnace as a source of heat and to the cooling chamber — a necessary adjunct to all brazing furnaces, as a means for cooling assemblies from the brazing temperature to 300 F or below. To a lesser degree, the prepared protective atmospheres that can be used most conveniently in furnace brazing, notably the exothermic-base and endothermic-base atmospheres, constitute another advantage when brazing deoxidized coppers and copper alloys in a furnace.

The rate of heating assemblies in a brazing furnace is low in comparison with the rates normally employed in torch, induction and resistance brazing. Few furnace heating cycles are less than five minutes in duration. For heating copper alloys susceptible to hot cracking, however, the slower, more uniform heating of a furnace is desirable.

In conveyor-type furnaces with multiple-zone heating chambers, the heating rate can be controlled with great accuracy. Depending on furnace capacity and the size of the assemblies to be brazed, the production rate in furnace brazing may equal or exceed that obtainable in induction brazing for the same amount of energy expended (assemblies per kilowatt-hour of input, for example).

The cooling rates that can be obtained in the cooling chambers of brazing furnaces can be closely controlled to ensure slow, uniform cooling. For copper alloys susceptible to hot cracking, the control of cooling rate from the brazing temperature is as important as control of the rate of heating to the brazing temperature.

Limitations. Apart from high initial equipment costs and the floor space required to accommodate a furnace with both a heating chamber and a cooling chamber (the length of the cooling chamber is usually at least three times that of the heating chamber), most of the limitations of furnace brazing are related to the deleterious effects of furnace temperatures and brazing fluxes on furnace muffles and linings, electrical heating elements, rails, trays, conveyor belts and other components. In general, these effects increase in seriousness as the operating temperature of the furnace increases. A furnace used for brazing copper and copper alloys with silver alloy filler metals and operating at a temperature below 1500 F could be expected to require considerably less maintenance, repair, and replacement of components than a similar furnace used to braze carbon steel with copper filler metals and operating at a temperature of 2000 F. The use of flux, required for brazing with most silver alloy filler metals, could offset the advantage of a lower operating temperature, however, by introducing corrosion and corrosive deterioration that are not encountered in a flux-free furnace chamber.

A furnace operating at 1500 F requires idling at elevated temperature when not in use, as does a furnace operating at 2000 F, thereby adding to power costs. Idling prevents thermal cycling that can cause serious damage to furnace brickwork and other components. Lower operating temperatures usually permit the use of lower idling temperatures. However, for furnaces operating with combustible protective atmospheres, the hazard of explosion is greatest when the furnace is operating at temperatures below about 1400 F, and special precautions must be scrupulously observed in this range (see the Appendix on Safe Operation of Brazing Furnaces, which begins on page 614 in this volume).

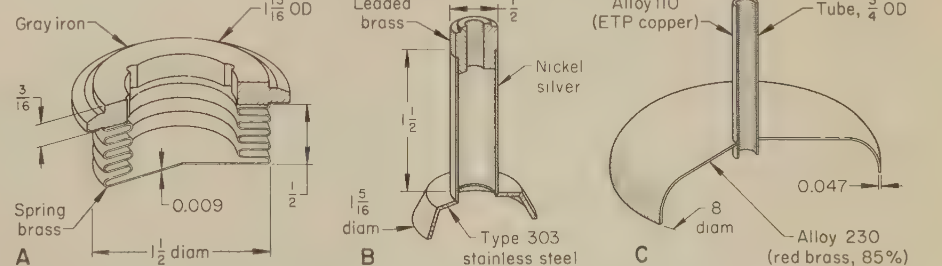
Furnaces. In terms of design and equipment, the furnaces used for brazing copper and copper alloys are essentially the same as those used for brazing steel (see pages 594 to 597 in the article on Furnace Brazing of Steel).

Table 2. Fluxes Used in Brazing of Copper and Copper Alloys

AWS type	Working temperature, F	Ingredients	Available forms	Base metals	Filler metals
3A	1050 to 1600	Boric acid Borates Fluorides Fluoborates Wetting agent	Powder Paste Liquid	All coppers and copper alloys except aluminum bronzes	BCuP and BAg series, except for BCuP-1 and BAg-19
3B	1350 to 2100	Boric acid Borates Fluorides Fluoborates Wetting agent	Powder Paste Liquid	All coppers and copper alloys except aluminum bronzes	All listed in Table 1
4	1050 to 1600	Chlorides Fluorides Borates Wetting agent	Powder Paste	Aluminum bronzes	BAg series (principally)
5	1400 to 2200	Borax Boric acid Borates Wetting agent	Powder Paste Liquid	All coppers and copper alloys except aluminum bronzes	RBCuZn series (principally)

Table 3. Comparison of Production Rates and Direct-Labor Costs for Brazing Three Different Assemblies by Different Processes

Assembly brazed (see drawings below)	Brazing process	Production rate, assemblies per hr	Direct labor: Rate per hour	Direct labor: Cost per assembly
A	Induction	720	$1.44	$0.002
A	Torch (manual)	120(a)	2.40	0.02(a)
B	Furnace	140	2.10	0.015
B	Torch (manual)	60(b)	2.40	0.04(b)
C	Induction	60(b)	1.44	0.024(b)
C	Furnace	12(c)	2.10	0.175(c)



(a) 30 sec for preparation and heating; one assembly at a time. (b) 60 sec for preparation and heating; one assembly at a time. (c) 5 min for preparation and heating; one assembly at a time.

Because of the damaging effects of sulfur and sulfur-bearing compounds on copper and copper alloys, the products of combustion in gas-fired furnaces operating without a muffle must be completely free of all traces of sulfur. Electric furnaces may be operated without a muffle unless damage caused by volatilized flux and flux droppings to brickwork and other furnace components warrants use of a muffle. Muffles may also be used to ensure the purity and to maintain the dew point of a protective atmosphere, particularly when the atmosphere is serving in place of a flux and its effectiveness depends on freedom from contamination. In the following example, which also describes a method for maintaining hole alignment between two components during furnace brazing, a nickel alloy muffle was used in the heating zone of an electric mesh-belt conveyor furnace to contain a purified hydrogen atmosphere.

Example 634. Use of a Nickel Alloy Muffle To Contain a Hydrogen Atmosphere Used in Place of a Flux (Fig. 1)

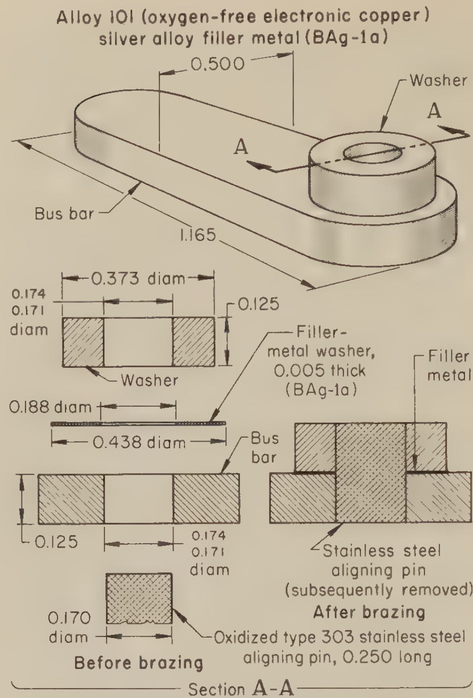
The electrical contact assembly shown in Fig. 1, a component of an aircraft power relay, was brazed in a continuous, electrically heated, mesh-belt conveyor furnace equipped with an Inconel alloy full muffle in the five-zone heating chamber. The muffle was filled with hydrogen supplied from a tank truck and subsequently dried in a palladium diffuser-purifier; the use of a pure, dry hydrogen atmosphere during brazing eliminated need for a brazing flux.

As shown in Fig. 1, the contact assembly was made by brazing a copper washer to a copper bus bar with a preformed 0.005-in.-thick silver (BAg-1a) filler-metal washer preplaced between the copper components. A major difficulty was to maintain hole alignment between the two components during the brazing cycle. This difficulty was overcome by inserting an aligning pin, made of an oxidized type 303 stainless steel, into each assembly. Assembly consisted of positioning the flat filler-metal preform over the hole in the bus bar, placing the copper washer on it, and then pressing the stainless steel pin through the hole. The oxide coating on the stainless pin prevented wetting of the pin by the filler metal; the coating was not reduced by the hydrogen atmosphere at the comparatively low brazing temperature (1260 F).

The assemblies were placed on the furnace conveyor belt and were carried through the five-zone heating chamber in an elapsed time of 9 min; after brazing, they were conveyed through the water-jacketed cooling chamber of the furnace, where they were cooled nearly to room temperature before leaving the furnace.

After brazing, the operator used a small tool similar to an arbor press to remove the pins. The assembly was then ready for the next operation, which consisted of resistance brazing a silver – cadmium oxide contact button to the end of the bus bar.

Visual inspection was used to determine that there was a small concave fillet of filler metal all around the joint. Sample lots were peel tested or sectioned. It was required that the area joined by brazing be not less than 80% of the area of the mating portions of the two components. Additional brazing details are given in the table with Fig. 1.



Conditions for Furnace Brazing

Furnace type	Mesh-belt conveyor(a)
Atmosphere	Hydrogen(b)
Filler metal	BAg-1a preform (see drawing)
Flux	None
Brazing temperature	1260 F
Production rate	350 assemblies per hour(c)
Gas cost	$3 per hour

(a) Five-zone, 17-kw electric furnace, with 4-in. by 4-in. Inconel alloy muffle. (b) Supplied from a tank truck and subsequently dried in a palladium diffuser-purifier before entering the furnace. Nitrogen, supplied from liquid bulk storage, was used for purging. (c) Limited by manual assembly.

Fig. 1. Electrical-contact assembly that was furnace brazed in a hydrogen atmosphere confined by an Inconel alloy muffle (Example 634)

Temperatures for furnace brazing depend primarily on the filler metal used, which in turn is necessarily related to the melting temperature of the base metal and to certain harmful effects, such as dezincification and hot-short cracking, that result from exceeding prescribed temperature limits. The brazing temperature selected is usually at least 50 F higher than the liquidus temperature of the filler metal and even higher brazing temperatures may be employed to promote fluidity or to achieve other desired results (as, for example, combining brazing and solution heat treatment in the same furnace operation). Some filler metals can be used at a temperature below the liquidus (BCuP-3, with a liquidus of 1485 F, and BCuP-5, with a liquidus of 1475 F, flow freely and make good joints at 1300 F; BCuP-5 was used at 1325 F in Example 599). In the next example, furnace brazing was done at 75 F below the liquidus of the filler metal (a silver-containing BCuP alloy), without using a protective atmosphere.

Example 635. Brazing at 75 F Below the Liquidus of the Filler Metal, Without Protective Atmosphere (Fig. 2)

The contact-arm assembly shown in Fig. 2 was a component of a line-voltage thermostat. The two contacts were made of fine silver and, when brazed to the copper arm, required a highly conductive joint to accommodate high service currents without overheating.

This application of furnace brazing was unusual because neither a flux nor a protective atmosphere was used and the brazing temperature was considerably below the liquidus of the filler metal. The copper-silver-phosphorus (BCuP-5) filler metal was self-fluxing on both copper and silver, and its unusually wide temperature range between solidus and liquidus (1190 to 1475 F) permitted brazing at a temperature below the liquidus. The assembly was brazed at 1400 F, 75 F below the liquidus temperature, in a mesh-belt conveyor furnace at a production rate of 377 assemblies per hour.

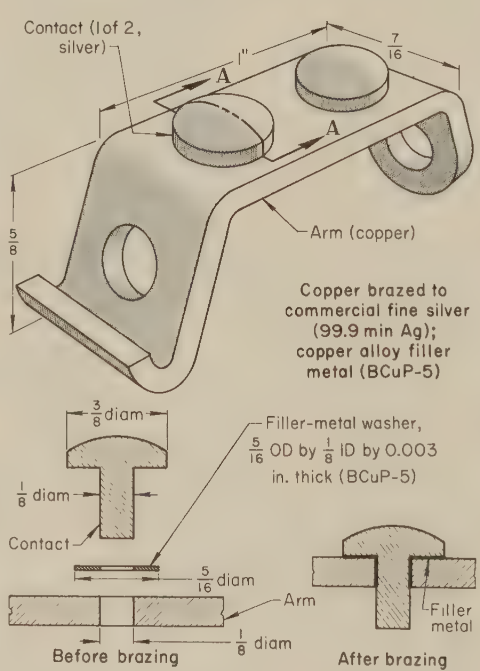


Fig. 2. Contact-arm assembly that was furnace brazed without protective atmosphere at 75 F below the liquidus of the filler metal (Example 635)

Accelerated Heating. Depending on the production rate required, and other factors, the maximum furnace temperature employed in a given brazing operation may vary considerably; it is not uncommon to employ a furnace temperature that exceeds that attained by the work load during the heating cycle in order to accelerate the heating rate and thereby to increase the production rate. Temperature differentials between the furnace thermocouple and the work being processed are usually established by experimentation and are controlled by regulating the elapsed time spent by the work load in the heating zone. At the higher furnace temperatures, and especially at temperatures above 1750 F, the substitution of a reducing protective atmosphere for a brazing flux will help to extend the life of heating elements and other furnace components by eliminating both oxidation and the corrosive reactions of volatilized flux. In the following example, assemblies were brazed at an accelerated heating rate in a prepared nitrogen-base atmosphere in a furnace equipped with a gastight muffle.

Example 636. Use of a Prepared Nitrogen-Base Atmosphere and an Accelerated Heating Rate (Fig. 3)

Figure 3 shows a bellows assembly consisting of a capillary tube of special DHP copper similar to alloy 122 but with a phosphorus content of 0.040 to 0.065%, a diaphragm plate of alloy 220 (commercial bronze, 90%), two diaphragms of alloy 172 (beryllium copper, 1.9%), and an extension point of alloy 340 (medium-leaded brass, 64.5%).

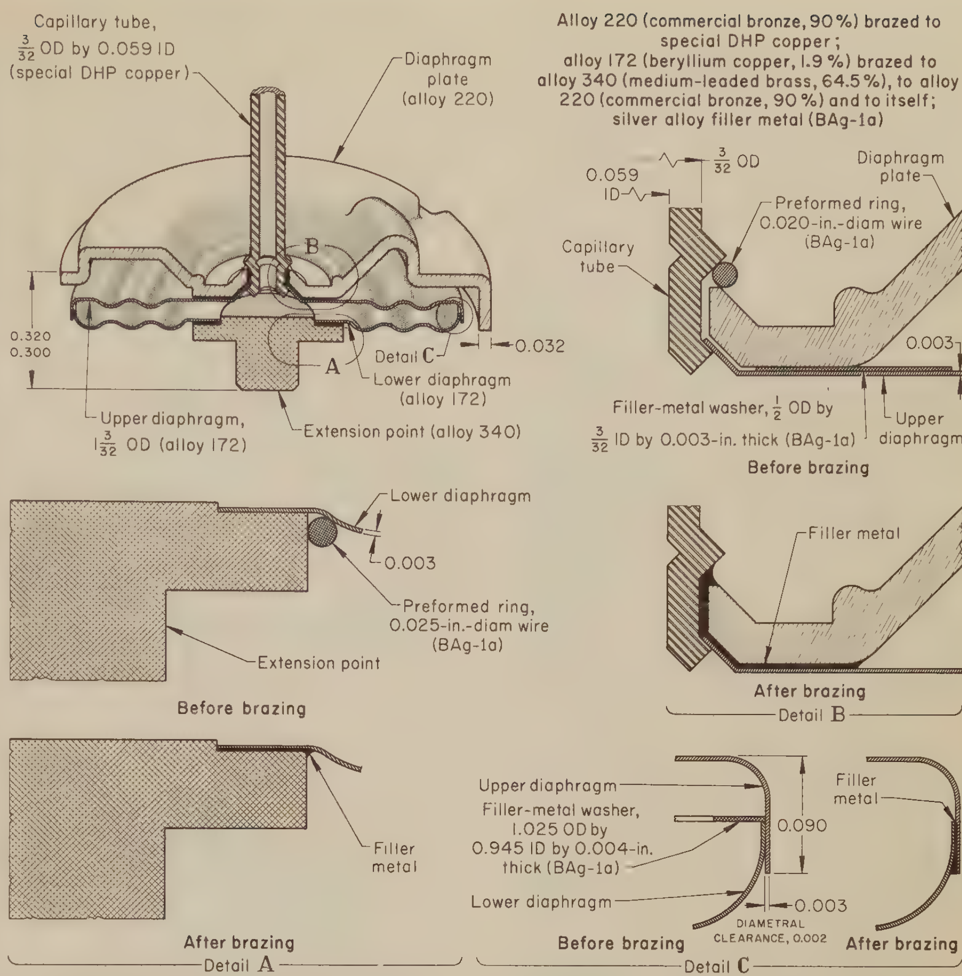
The upper diaphragm, the diaphragm plate, and the capillary tube were assembled as shown in detail B in Fig. 3, using two preforms — a ring of 0.020-in.-diam BAg-1a wire that fit over the tube, and a ½-in.-OD washer of 0.003-in.-thick BAg-1a filler metal with a 3⁄32-in.-diam center hole to accommodate the capillary tube. The tube was staked in two places to hold the subassembly together.

The lower diaphragm was assembled with the extension point, using a preformed ring of 0.025-in.-diam BAg-1a wire that fit snugly over the extension point (see detail A in Fig. 3). The diameter of the lower diaphragm was such that the lower diaphragm would fit snugly into the upper diaphragm. A preformed washer of 0.004-in.-thick BAg-1a filler metal was fitted into the cavity between the two diaphragms (see detail C in Fig. 3).

Originally, the assembly had been brazed in a brick-lined muffle furnace using an exothermic-base protective atmosphere. With this atmosphere, use of a flux was required. Although this was an inexpensive brazing method, the cost of removing the flux had to be added to the cost of the brazed product, and belt life was ⅛ to 1⁄12 that of belts operated in a furnace without using a flux.

To eliminate the difficulty and cost of removing flux and to obtain acceptable belt life at a high production rate, the brazing procedures were changed. The assemblies (without flux) were placed on the 12-in.-wide mesh belt of an electrically heated conveyor furnace. They traveled through the furnace at 30 in. per minute. Although the furnace was heated to 1800 F, to accelerate the rate of heating of the work, the assembly joints did not reach a temperature higher than 1175 F. The final adjustment of conveyor speed was determined by visual observation of filler-metal flow, rather than by recorded temperature of a thermocouple bead.

The furnace was equipped with a gastight Inconel alloy muffle. The protective atmosphere that eliminated the use of flux was a prepared nitrogen-base atmosphere containing 75% nitrogen and 25% hydrogen and having a dew point of −80 F or lower, obtained by processing the gas in a molecular-sieve drying tower. The atmosphere entered the furnace near the center and exited at both ends, where it was burned. The assemblies were cooled to 300 F before leaving the cooling chamber of the furnace. Production was 1200 assemblies per hour.



Conditions for Furnace Brazing

Furnace type	Electric mesh-belt conveyor(a)	Flux	None
Atmosphere	Nitrogen-base (75% N_2, 25% H_2)	Brazing temperature	1175 F(b)
Filler metal	BAg-1a preforms (see drawing)	Production rate	1200 assemblies per hour

(a) Furnace was equipped with a gastight Inconel muffle. Conveyor belt was 12 in. wide and moved at 30 in. per minute. (b) Furnace temperature was 1800 F, but the conveyor speed was high enough to ensure that assemblies did not reach a temperature of more than 1175 F.

Fig. 3. Bellows assembly, of copper and three different copper alloys, that was furnace brazed in a prepared nitrogen-base atmosphere at an accelerated heating rate (Example 636)

Furnace Atmospheres. Protective atmospheres are commonly used in the furnace brazing of copper and copper alloys, although there are numerous exceptions (see Example 635). Exothermic-base, endothermic-base, dissociated ammonia and other suitable prepared atmospheres are widely used to protect copper and copper alloys that are not adversely affected by hydrogen-containing gas mixtures at elevated temperature. Atmospheres and maximum dew points generally recommended for brazing copper and copper alloys are given in Table 4. Additional information on these atmospheres is given in the section on Protective Furnace Atmospheres in the article on Furnace Brazing of Steel (page 597). Detailed information regarding the generation of exothermic-base, endothermic-base, and dissociated ammonia atmospheres is given in the article "Furnace Atmospheres", on pages 67 to 84 in Volume 2 of this Handbook.

As shown in Examples 634 and 636, it is sometimes possible, depending on base-metal and filler-metal combinations, to avoid the use of a brazing flux by brazing in either a dry hydrogen or a prepared nitrogen-base atmosphere. These are among the more expensive furnace atmospheres; however, at low dew points, they have the advantage of being highly reducing. Prepared exothermic-base atmospheres are considerably less expensive and are effective in preventing oxidation at elevated temperature, but the reducing potential of these atmospheres is limited because hydrogen content does not exceed about 13%, and consequently they cannot be used as a substitute for a chemical flux. In the following example, nickel silver tableware handles were furnace brazed in a prepared exothermic-base atmosphere, using a silver alloy filler metal and chemical flux.

Table 4. Recommended Protective Atmospheres for Furnace Brazing of Copper and Copper Alloys

Base metal(a)	Suitable atmospheres	Maximum dew point, F
Coppers and phosphor bronzes	Lean or rich exothermic	20
	Reacted endothermic	20
	Dissociated ammonia	20
Red brasses (low zinc)	Purified, lean exothermic	10
	Reacted endothermic	10
	Dissociated ammonia	20
Yellow brasses (high zinc), leaded brasses, tin brasses (high zinc)	Purified, lean exothermic	−40
	Reacted endothermic	−20
	Dissociated ammonia	20
Silicon and aluminum bronzes	Purified, lean exothermic	−40
	Dissociated ammonia	−40
Copper nickels	Lean or rich exothermic	20
	Reacted endothermic	20
	Dissociated ammonia	20
Nickel silvers	Purified, lean exothermic	−40
	Reacted endothermic	−20
	Dissociated ammonia	20

(a) See pages 338 and 476 for alloy classifications and properties.

Example 637. Brazing Nickel Silver in an Exothermic-Base Atmosphere, Using a Conventional Flux (Fig. 4)

A filler metal containing 75% silver, 22% copper and 3% zinc was used to braze the nickel silver tableware handles like the one shown in Fig. 4. The handles were brazed in an electrically heated mesh-belt conveyor furnace using an exothermic-base atmosphere, using a type 3A flux.

The handles were made of alloy 757 in two different stock thicknesses, 0.025 and 0.040 in. The halves of the hollow handle were formed by dies in a drop hammer in two stages — breakdown and final shaping. The cut and fractured edges of the halves were smoothed on a belt grinder, after which a light coating of type 3A flux was applied to the edges with a rubber roller.

The halves were assembled and held together by lightweight stainless steel fixtures that contacted the halves near their midpoints rather than at the joint line, thereby maintaining joint clearance at 0.002 in. or less. One piece of filler-metal wire weighing 0.009 troy oz was dropped into each assembly, and the assemblies were placed on two nonmetallic bars in a rack. The racks were then placed on the conveyor belt of the brazing furnace. The assemblies were in the high-temperature (1650 F) zone of the furnace for approximately 9 min, after which they passed through the cooling zone. They were washed in hot water to remove the flux as soon as they were discharged from the cooling zone.

The high-silver alloy was expensive, but because very little was used for an assembly, filler-metal cost was insignificant. This alloy was selected for its excellent flow characteristics and was required to braze a joint more than 9 in. long with an absolute minimum amount of wire. Brazing at 1650 F, instead of at a lower temperature, reduced the number of rejects and increased the amount of alloying.

Assembly for Brazing. The component parts to be furnace brazed must be assembled in an essentially fixed position, with filler metal preplaced, before entering the furnace, and they must be capable of maintaining this position throughout brazing and cooling. Self-jigging is the preferred method of assembly. An assembly is self-jigging when its component parts incorporate design features that will ensure that each component, when assembled, will remain in proper relationship throughout the brazing cycle without the aid of auxiliary fixtures. Self-jigging can be accomplished by numerous methods (see page 603 in this volume).

When self-jigging is not feasible or when the assembly requires positioning or support in addition to that provided by self-jigging, auxiliary fixtures are used. These fixtures may take the form of a simple bracket or wire stand, ceramic blocks, clamps, or cast supports.

Venting Fully Enclosed Assemblies. Fully enclosed assemblies, whether assembled by self-jigging or supported by auxiliary fixturing, must be vented to permit the escape of entrapped air. When heated, entrapped air expands and, unless adequately vented, escapes from a sealed assembly in the area of the joint, resulting in flux spatter, joint porosity, and misalignment of brazed components. A small pinhole or slot, located near the top of the assembly but safely away from the area of the joint, is usually sufficient to provide adequate venting and to avoid damage to the joint. A more ingenious, though simple, method of venting is described in the following example.

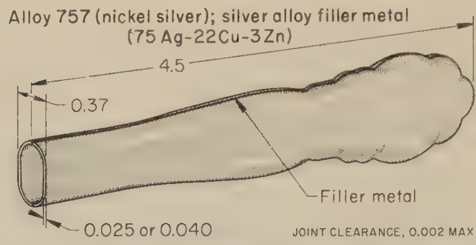


Fig. 4. Hollow tableware handle made by furnace brazing two formed halves under protection of exothermic-base atmosphere (Example 637)

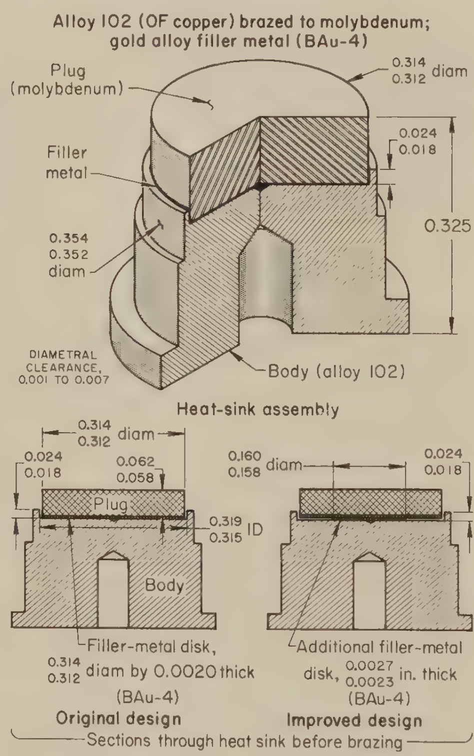
Example 638. Improved Venting by Use of an Additional Filler-Metal Preform (Fig. 5)

The heat-sink assembly shown in Fig. 5, which was used in an electrical circuit, was made by furnace brazing a molybdenum plug into a 0.315/0.319-in.-diam recess at the top of an alloy 102 (oxygen-free copper) body. The brazed assembly was subsequently plated.

Originally, the assembly was brazed using a single preformed disk of BAu-4 gold alloy filler metal of the same diameter as the plug (0.312/0.314 in.) and of almost the same diameter as the recessed hole, and 0.0020 in. thick (about one-tenth the depth of the recessed hole). With this design, there was no escape route for entrapped air, which expanded when heated and, at brazing temperature (1800 F), bubbled through the molten filler metal, leaving either small visible vent holes or invisible voids — depending on the viscosity of the molten metal when the bubble was formed. (Voids and vent holes trap liquids that eventually cause corrosion and, in electrical equipment, adversely affect the functioning of components.)

The visible vent holes were cause for immediate rejection; the voids, which were hidden under a thin skin, resulted in added expense, because often they were not discovered until the plating operation, when the preliminary acid cleaning opened the defect.

To improve venting, an additional disk of BAu-4 filler metal, 0.158/0.160 in. in diameter, was placed under the larger-diameter first disk to raise it and the molybdenum plug and allow passage of entrapped air (see "Improved design" view in Fig. 5). Results of the venting improvements, in terms of the percentage of rejections after brazing and at plating inspection, are given in the table with Fig. 5. Additional brazing conditions are also given in the table appearing with Fig. 5.



Conditions for Furnace Brazing

Furnace type	Electric mesh-belt conveyor(a)
Atmosphere	Dry hydrogen
Filler metal	BAu-4 disks (see drawing)
Flux	None
Brazing temperature	1800 F

Inspection	Original design(b)	Improved design(c)
Rejection Rate for Voids and Vent Holes		
After brazing	2%	1.6%
At plating	21.4%	3.7%

(a) Three zone; entrance and cooling zones were water-cooled. Muffle cross section was 6 by 8 in. (b) 100 assemblies inspected. (c) 350 assemblies inspected.

Fig. 5. Furnace brazed heat-sink assembly for which the use of an additional, smaller-diameter disk of filler metal provided adequate venting (Example 638)

Torch Brazing

Torch brazing of copper and copper alloys follows the same basic principles and uses the same equipment as the torch brazing of steel (see the article on Torch Brazing of Steel, which begins on page 619). The properties of copper and copper alloys introduce certain specific considerations in torch brazing.

Applications. Joining components of various types of heat exchangers probably represents the largest field of application for torch brazing of copper and copper alloys; products include condensers, evaporators, air conditioners, radiators and refrigerators, all of which depend on the high thermal conductivity of copper. Torch brazed products that depend on the high electrical conductivity of copper include motor windings, reactor coils, switches, contactors and terminal leads.

Process Selection. The selection of torch brazing in preference to another brazing process, such as furnace or induction brazing, depends largely on feasibility and cost. In seven of the ten examples of torch brazing presented in this article, brazing by any other process was not feasible because of workpiece limitations.

Manual Torch Brazing. Low equipment cost is a major advantage in manual torch brazing, which is particularly useful for assemblies involving unequal masses. A brazer with moderate skill can adjust and apply the heating flame so that unequal masses will be brought uniformly to brazing temperature. Similarly, the brazer can apply the heat selectively to the joints of assemblies involving both large and small areas. The size of brazing flames may range from those of extremely small torches the size of a hypodermic needle, employed for electronic leads (see Example 648), up to those of large torches used in brazing assemblies weighing hundreds of pounds.

In the example that follows, manual torch brazing was used because of the number of joints, the need for differential heating because of variations in mass, and the small production run.

Example 639. Manual Torch Brazing of 32 Joints in a Heat-Exchanger Assembly (Fig. 6)

The heat exchanger shown in Fig. 6 required 32 brazed joints. Thirty tubes made of admiralty brass (uninhibited) were torch brazed to a red brass tube sheet, which then was torch brazed to a cast housing end of leaded red brass. The casting in turn was torch brazed to a yellow brass housing tube.

The various joints were brazed with a filler metal containing 92% copper and 8% phosphorus — similar to BCuP-2 and used for brazing in the range of 1350 to 1400 F.

In some of the products, the fluid to be used in the heat exchanger (such as transmission oil) was not compatible with the copper-phosphorus filler metal, and a filler metal containing at least 35% silver, such as BAg-2, was used.

Because of product complexity and the variety of joints and joint locations, manual torch brazing was the most practical method of joining the assembly.

Base-Metal Alloys. Although nearly all coppers and copper alloys can be brazed, the ones most often torch brazed are the oxygen-free coppers and the copper-zinc alloys (see page 338). The base metals dealt with in examples of torch brazing in this article are:

Alloy No.	Alloy name	Example No.
102	Oxygen-free copper	640
122	Deoxidized copper (DHP)	642, 643
172	Beryllium copper, 1.9%	645
230	Red brass, 85%	639
260	Cartridge brass, 70%	645
268	Yellow brass, 65%	639, 641
360	Free-cutting brass	645
442	Admiralty, uninhibited	639
715	Copper nickel, 30%	647
(SAE 40)	Leaded red brass (cast)	639

Several precautions should be taken when torch brazing certain coppers and copper alloys. Where it is necessary to braze oxide-containing (tough pitch) coppers, a reducing atmosphere in the flame should be avoided because it will promote hydrogen embrittlement. For these coppers, a neutral or slightly oxidizing flame and a short brazing cycle are advisable. The brasses are subject to volatilization of zinc when overheated or when held too long at brazing temperature.

Alloys containing elements that readily form refractory oxides (aluminum, beryllium, chromium and silicon) should be protected by flux and should not be exposed to an oxidizing flame.

One of the notable differences between the torch brazing of steel and the torch brazing of copper alloys is that steel can withstand very rapid heating rates whereas some of the copper alloys (the phosphor bronzes, for instance) are subject to cracking if heated too rapidly when the metal is under high restraint during brazing.

Filler metals commonly used for torch brazing of copper and copper alloys include the lower-melting BAg silver alloys, the lower-melting BCuP copper-phosphorus alloys, and the copper-zinc filler metal RBCuZn-A.

The BAg-1 and BAg-1a alloys have the lowest melting temperatures of all the filler metals used in torch brazing of copper and copper alloys, and possess excellent flow characteristics. These filler metals contain more silver than BAg-2 (see Table 1), and are therefore more costly. For this reason,

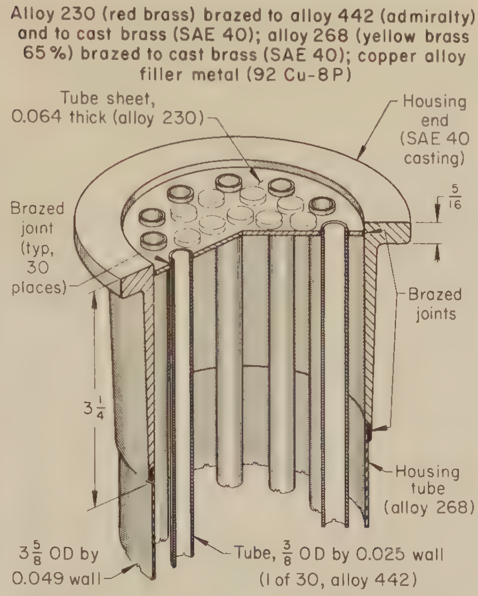


Fig. 6. Heat exchanger for which manual torch brazing was selected because of the number of joints (32), the need for differential heating, and the low production quantity (Example 639)

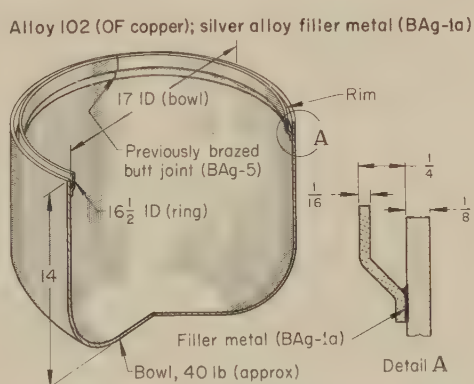
BAg-2 is sometimes preferred, even though it has a higher liquidus temperature than BAg-1 or BAg-1a.

Differences in the brazing-temperature ranges of various filler metals are used for step brazing; see page 648 in the article on Resistance Brazing and Example 599, as well as the example of silver brazing that follows.

Example 640. Use of Torch Silver Brazing for Low Production of a Bulky Assembly (Fig. 7)

The copper rim that was brazed to the inner edge of a copper bowl as shown in Fig. 7 formed a groove into which an end cap was later soldered. The brazed joint of this assembly had to be leaktight to a gas pressure of 15 psi.

The assembly was torch brazed without the use of a holding fixture. Heating was done with an oxy-natural gas torch. The



Conditions for Torch Brazing Rim to Bowl

Cleaning	Degrease and bright dip
Fixture	None(a)
Torch tip	3/16-in.-diam orifice
Fuel	Natural gas, 10 psi; oxygen, 70 psi
Filler metal	3/32-in.-diam BAg-1a(b)
Flux	Type 3A

(a) A gage was used to locate rim depth. (b) 2 oz per assembly.

Fig. 7. Bowl-and-rim assembly joined by torch brazing without the use of a fixture (Example 640)

sequence of operations was as follows: The rim was made by forming a 1/16-in.-thick by 1-in.-wide copper strip into a ring with a major outside diameter of 17 in. and butt brazing the ends with BAg-5 filler metal. The rim and bowl were degreased and bright dipped before being brazed together. The joint surfaces were brushed with a type 3A brazing flux. The rim was fitted to the bowl, using a gage to maintain proper depth, locally heated and tack brazed, using BAg-1a filler metal. Then the bowl was torch heated and the joint was brought to brazing temperature, the braze being completed by hand feeding BAg-1a filler metal. BAg-1a filler metal was used because of its low melting point, ability to make leaktight joints, and ability to withstand a subsequent forming operation. Also, the BAg-1a alloy was easily wetted by the tin-lead solder used when the end cap was joined to the bowl. BAg-5 filler metal was used to butt braze the ends of the rim because this alloy has a solidus temperature higher than the liquidus temperature of BAg-1a. Therefore, the butt-brazed joint was not affected during subsequent brazing of the rim to the bowl. Additional conditions for torch brazing the rim to the bowl are given in the table with Fig. 7.

The color of silver alloys does not match that of most copper alloys. Joints that are visible are plated or painted if appearance is important. Face-fed filler metal in the form of wire, powder, or a paste with flux is less neat in appearance than filler metal deposited from preplaced preforms. The latter, made from either wire or strip, are used in deep joints or in joints having a change in direction of the mating surfaces. The following example describes a production part that made use of preplaced filler-metal preforms, and that later was plated.

Example 641. Torch Brazing a Three-Piece Faucet Assembly With Silver Alloy Filler Metals (Fig. 8)

The brazed faucet assembly shown in Fig. 8 replaced a casting. This assembly was brazed from three alloy 268 (yellow brass, 65%) components, using radiant heat from two open gas burners, with integral reflectors, that burned natural gas and air. The mixing manifold and the spout were made in an automatic bar machine; the tube that connected them was made by drawing. The brazing operation was manual, although the burners were fixed.

Two identical fixtures were used for brazing, so that one assembly could be loaded while the other was being brazed. The spout end of the assembly took two preforms of BAg-1 filler metal: one, a piece of 0.003-in.-thick strip 1 in. long by 3/8 in. wide; the other, a 120° ring segment made of 0.047-in.-diam wire and formed to a 1/2-in. internal radius (see view at lower left and section B-B in Fig. 8). The mixing-manifold end of the assembly took a single preform made of 0.050-in.-diam BAg-1 wire in the form of a 60° segment of a ring with an inside radius of 7/8 in. (see view at lower left and section A-A in Fig. 8). Both joints were fluxed with type 3A flux. The fixtures were placed for brazing so that the radiant gas burners were at each end of the assembly, thus brazing both joints at the same time. Brazing temperature was approximately 1200 F. After brazing, the assemblies were cooled to about 600 F in air and then immersed in water to remove flux residue. Production rate was 70 assemblies per hour.

The brazed assemblies were leak tested by submerging them in water and applying air pressure at 90 psi. They were then decorative chromium plated. The brazed joints were invisible under the plating.

The BCuP filler metals contain phosphorus, which makes them self-fluxing

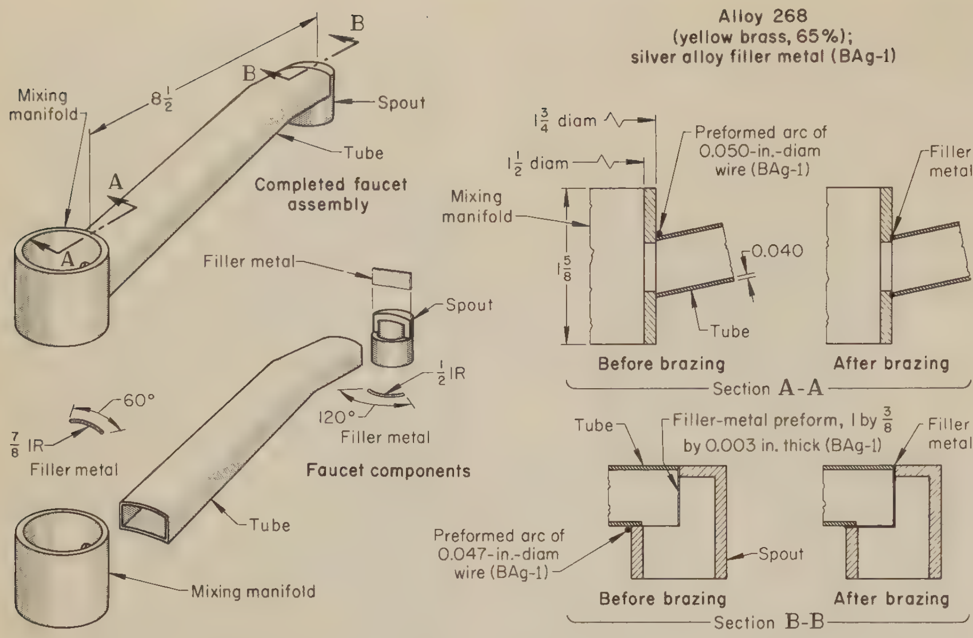


Fig. 8. Torch brazed faucet assembly that replaced a complex casting (Example 641)

on copper, but when these filler metals are used with copper alloys, a type 3A flux is usually advisable or necessary. These are the only filler metals used in torch brazing of copper and copper alloys that cannot be used on steel (because of the formation of brittle iron phosphides). When heated for too long a period, these alloys will liquate to an extent that will cause a decrease in joint strength. Rapid heating is therefore advisable.

Of the types used in torch brazing, BCuP-2 and 4 are the most fluid, and will fill joints having diametral clearances of 0.001 to 0.003 in. BCuP-5 will tolerate looser fits; typical diametral clearance is 0.001 to 0.005 in. The BCuP alloys are lower in cost than the silver alloy filler metals, and also provide a better color match on copper when the oxide film that forms on the filler metal during cooling has been removed. The next two examples describe the use of BCuP-5 in torch brazing.

Examples 642 and 643. Use of Self-Fluxing Filler Metal (BCuP-5) in Torch Brazing Copper Assemblies

Example 642 — Return Bends for a Heat Exchanger (Fig. 9). Return bends were brazed to heat-exchanger tubes as shown in Fig. 9. The tubes and return bends were of alloy 122 (phosphorus-deoxidized copper, DHP), ⅜-in. OD, with 0.016-in. and 0.020-in. wall thicknesses, respectively. Ends of the tubes were expanded to fit over the ends of the return bends with diametral clearance of 0.004 to 0.009 in. Brazed joints had to be leaktight at 400-psi pressure.

All parts were vapor degreased before brazing. Each leg of the return bends was mechanically fitted with a preformed ring of 0.030-in.-diam BCuP-5 filler wire, which does not require a flux when used for brazing copper. It was necessary that the wire ring fit tightly on the tube, so that the filler metal would be heated by conduction as the base metal was heated to brazing temperature. If heated directly, the filler metal might have melted before the base metal reached brazing temperature.

The joints were assembled and manually brazed using a Y-shape oxyacetylene torch with two tips (Fig. 9). The opposing tips surrounded the joint with flame, making heating faster and more uniform than it would have been with only one flame. The joint was brought up to temperature as rapidly as possible to prevent liquation of the filler metal. Each joint took 5 sec to braze. Since no flux was used, the brazed joints did not have to be cleaned.

The manufacturer also used multiple-flame gas-air burners for this type of product. Such equipment was used for high production on a given size of return bend. Multiple burners heated both joints at one time while the assemblies were on a conveyor line. Natural gas was used in preference to acetylene for economy and heating control; some joints were overheated and others underheated when using the rapid heating of acetylene. Radiant-type gas burners were also suitable for this type of work. Furnace brazing could not be used, because it was not permissible to heat the remainder of the assembly, including the aluminum fins. For this application, localized heat was essential.

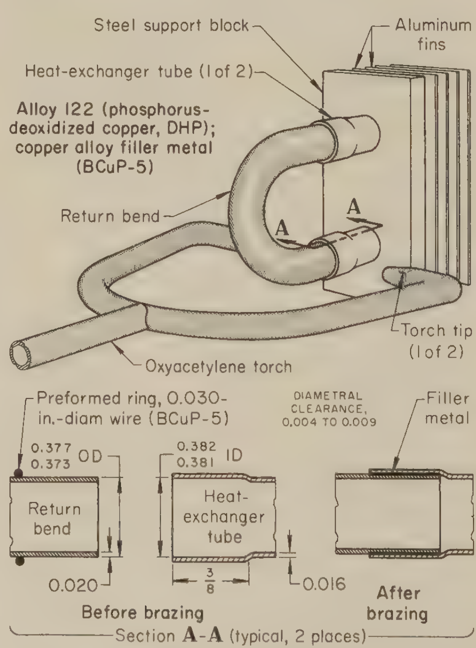


Fig. 9. Return-bend assembly of a heat exchanger, and a dual-tip torch used for rapid heating of the self-fluxing filler metal (Example 642)

Example 643 — Fin-Tube Assembly (Fig. 10). Circular cooling coils were made of two nested counterflowing segments coupled by a return bend (Fig. 10). Each coil segment consisted of 5½ turns of alloy 122 (phosphorus-deoxidized copper, DHP) tubing, 0.629 ± 0.005-in. ID by 0.042-in. wall, fitted with closely spaced fins about 1⁹⁄₁₆-in. OD. Four brazed joints were required, two at the return bend and one each at the inlet and outlet elbows. The return bend and elbows, also of alloy 122, were formed from ⅝-in.-OD by 0.042-in.-wall tubing. The diametral clearance for brazing varied from 0.002 to 0.005 in.; because of tubing tolerances, the return bends and the elbows were dressed as required, to obtain clearance within this range. The assembly had to be leaktight under 250-psi air pressure.

Manual torch brazing was selected as the most practical method of brazing the assemblies because (*a*) annual production was not high, (*b*) the workpiece was large compared with the joints to be brazed, (*c*) some manipulation of the assembly was needed, and (*d*) localized torch heating offered flexibility and freedom from general distortion.

The components were vapor degreased after forming. The two coil segments were then positioned in a rack consisting of four steel uprights (1-in. by ¼-in. steel flats) mounted on a circular base. A 0.109-in.-diam rod of the self-fluxing brazing alloy BCuP-5 was selected for filler metal to eliminate the need for flux application and removal. An available protective atmosphere (a furnace gas containing 1 to 2% CO, 10 to 12% CO_2, remainder nitrogen) was piped through the tubing during brazing to protect the internal surfaces from oxidation.

The joints were heated to brazing temperature with a manual oxy-natural gas torch, the natural gas being supplied at approximately 1 psi. The filler metal was face fed. The return-bend joints were brazed first; then the inlet and outlet elbows were correctly positioned and brazed. After brazing, the coil was strapped with flat brass bars and bolts and removed from the holding rack. Production rate averaged about 1½ assemblies per hour.

The BCuP filler metals are supplied as wire, rod and powder. BCuP-1 and BCuP-5 alloys are also available as strip. Like several other filler metals available in strip or sheet form, BCuP-5 is also produced by some manufacturers as a clad sheet ("brazing sheet") having a copper core and a cladding of BCuP-5 alloy on both sides. Clad brazing sheet is cut into strips and placed in joints or on surfaces that cannot be filled with other forms of filler metal. An application that made use of a special strip clad with BCuP-5 is described in Example 648.

The copper-zinc filler metal used in torch brazing is RBCuZn-A, which has the highest brazing temperature range of the filler metals considered here. Overheating must be avoided, both to protect the base metal and to prevent voids in the braze due to vaporization of the zinc.

Corrosion resistance is a consideration in selection of filler metal. Filler metal of inferior resistance can be selectively attacked. For example, RBCuZn-A is inferior in corrosion resistance to copper, copper-silicon and copper-nickel alloys. The silver alloy brazing filler metals have good corrosion resistance. For the brazed heat exchangers discussed in Example 639, 92Cu-8P filler metal was not satisfactory when the heat-exchanger fluid was a transmission oil, and a silver alloy filler metal was required.

Fluxes. Selection of flux for torch brazing of copper and copper alloys depends not only on the filler metal used (as it does for brazing of steel), but also on the base metal. Some copper alloys form refractory oxides, and this influences choice of flux.

When a silver alloy filler metal is used in brazing copper, or in brazing a copper alloy that contains no elements that cause it to form refractory oxides (aluminum, beryllium, chromium and silicon), a type 3A flux is used. The same flux is used when brazing these alloys with a BCuP filler metal. When brazing the copper alloys that do form refractory oxides, a more active flux is usually required. For instance, the aluminum bronzes require a type 4 flux to inhibit the oxidation of aluminum.

"Gas fluxing", by entraining volatilized flux in the gas flame, is used in torch brazing copper and copper alloys. The equipment for and use of this fluxing method are described on page 629 in the article on Torch Brazing of Steel. When used on copper and its alloys, the purpose of gas fluxing is to protect the surface of the base metal from becoming oxidized or discolored. It thus eliminates postbraze cleaning. Joint surfaces are always first protected with an appropriate flux. This secondary use of a gas flux is illustrated in the following example.

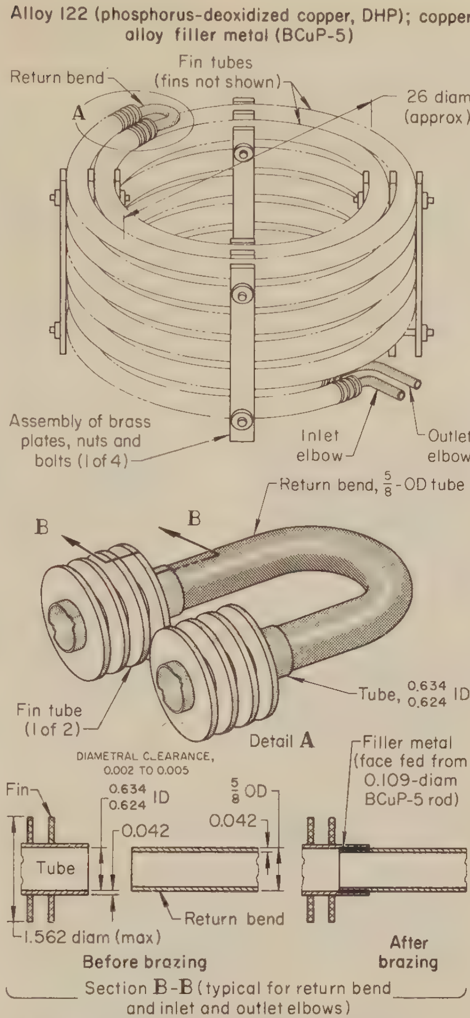


Fig. 10. Fin-tube assembly showing four joints that were manually torch brazed using self-fluxing filler metal (Example 643)

Example 644. Use of Gas Fluxing To Prevent Oxidation of Work Metal During Brazing (Fig. 11)

Two types of flux were used when torch brazing a capillary tube system consisting of a bulb and two capillary tubes (Fig. 11). One type was necessary for brazing. The other, a gas flux fed through the flame, was used to prevent oxidation and discoloration of the copper assembly. The torch used oxyacetylene and had a standard brazing tip and conventional gas-fluxing equipment. The gas flux was composed of 71½% methyl borate and 28½% acetone. BAg-1 filler metal was used, although other filler metals, such as BAg-1a and BCuP-2 to 5, would have been satisfactory.

After five assemblies had been loaded on a five-station manually operated fixture, the joint surface of each tube was brushed with a small amount of type 3A flux to ensure penetration of flux and filler metal into the joint. The joint was heated with the oxyacetylene flame containing the gas flux. The torch was passed up and down over the assembly to give it a flux coating, to prevent oxidation during brazing. The torch was then held close to the bulb to ensure even heating, because the bulb portion had the thicker wall. The filler metal was hand fed to complete the joint. The brazed assembly was removed and quenched with water to cool it and remove the flux. This sequence of operations was repeated for each of the five assemblies in the fixture. The finished assembly was bright and free of deposits.

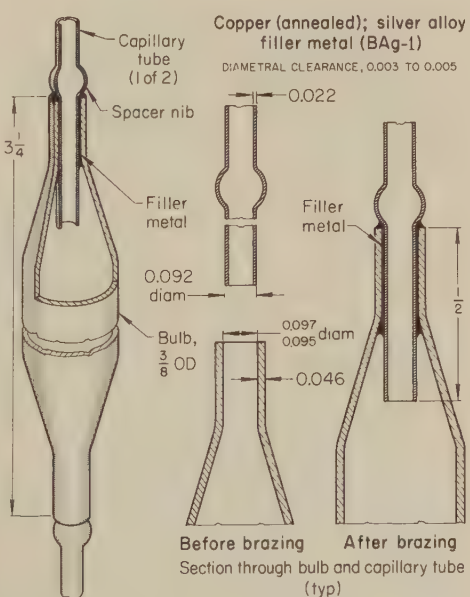


Fig. 11. Bulb and capillary tubes joined by torch brazing, using gas fluxing to prevent oxidation, in addition to a type 3A brazing flux (Example 644)

Fuel Gases. The fuel-gas mixtures generally used in torch brazing of copper and copper alloys are oxyacetylene, oxy-natural gas, oxy-propane, oxy-hydrogen and air–natural gas. The oxy-fuel gases are highest in cost, flame temperature and heating rate, with oxyacetylene the highest in the group in each respect. Oxy-fuel gases are widely used in manual torch brazing, where temperature can be controlled by torch manipulation. The cost advantage of air–natural gas is exploited particularly in mechanized and automatic high-production torch brazing, where the lower flame temperature affords protection from damage due to overheating. Desired heating rates are obtained economically by using high flow rates, together with multiple torches or radiant-type burners.

Neutral or slightly reducing flames are used to help the fluxes in preventing oxidation of base-metal surfaces.

Although high heat input is necessary to overcome their high thermal conductivity, many copper alloys cannot withstand the rapid heating rates that can be used on steel. Under too rapid heating, high thermal expansion can cause local stresses, resulting in distortion and cracking in some alloys. Accidental overheating will cause damage to copper and copper alloy assemblies more readily than to those made of steel. The use of gases of lower flame temperature requires less skill in avoiding these difficulties.

Although the use of oxyacetylene flames requires more care to avoid overheating than does the use of other types of flames, oxyacetylene flames heat faster. In the following example, oxyacetylene was well suited to the purpose of bringing the joints to temperature quickly in order to localize the heat to avoid loss of the effects of cold work, and to keep labor costs low.

Example 645. Torch Brazing of Five Copper Alloys and a Stainless Steel in a Bourdon-Tube Spring Assembly (Fig. 12)

The measuring element of a 5000-psi pressure gage was a bourdon tube made of alloy 172 (beryllium copper, 1.9%), coiled to form a spring that deflected under internal pressure. The spring assembly, shown in Fig. 12, required four brazed joints. Section A-A in Fig. 12 shows two joints that were brazed simultaneously: a type 304 stainless steel capillary tube brazed to a copper bushing, which was brazed to the inside of the beryllium copper bourdon tube. At section B-B, in Fig. 12, the bourdon tube was brazed to a take-off arm of alloy 360 (free-cutting brass), which in turn was brazed to a take-off lug of alloy 260 (cartridge brass, 70%), as shown in section C-C in Fig. 12.

Torch brazing was used because it was simpler to control the amount of heat input required for the different joints by torch than by induction brazing. Furnace brazing was considered unsatisfactory because the entire spring would have been exposed to the brazing temperature, which would have removed the effects of cold work and thus have reduced the potential mechanical properties obtainable by the heat treatment after brazing.

A fixture was used to position the components accurately for brazing. The parts were fluxed with type 3A flux, assembled in the fixture, and heated by an oxyacetylene torch. Silver alloy filler metal (BAg-1a) was hand fed to the joints. Immediately after the filler metal had solidified and while the assembly was still hot, it was plunged into cold water to remove the flux residue, and to limit the annealing action on the beryllium copper bourdon tube.

After brazing, the springs were age hardened and then bright dipped. Each assembly was made, quenched and dried, ready for heat treatment, in 2.25 min. At $3 per hour, this represented a direct labor cost per piece of $0.113.

Mechanized and automatic torch brazing equipment and operations are the same as those applied on steel assemblies, except for the special considerations discussed earlier in this section. Mechanized and automatic torch brazing of steel is discussed on pages 623 to 627 in this volume.

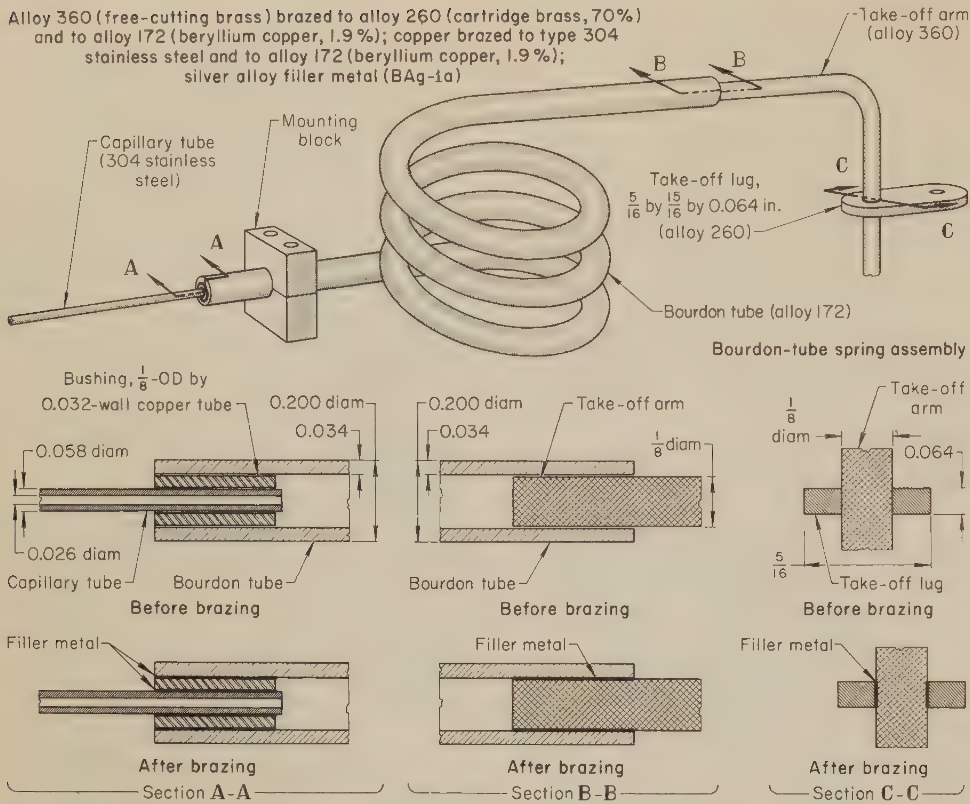


Fig. 12. Torch brazed bourdon-tube spring assembly with components of five different copper alloys and a stainless steel (Example 645)

Mechanized torch brazing is most widely used in the manufacture of air conditioners, radiators and other types of heat exchangers that utilize hairpin coils of copper tubing with aluminum fins. Conveyor belts and turntables are used extensively for both mechanized and automatic torch brazing. The following example illustrates the use of a turntable in an operation that was wholly automatic except for assembly.

Example 646. Use of an Eight-Station Turntable for Automatic Brazing of Bulb-and-Tube Assemblies (Fig. 13)

The eight-station automatic setup shown in Fig. 13 replaced a manual torch brazing setup that required two operators and utilized a rotating fixture for brazing copper bulb-and-tube assemblies. Production rate (about 700 joints per hour, gross) was not increased with the automatic method, and improvement in quality was negligible. However, only one unskilled operator was needed for the automatic method. Therefore, the cost of direct labor was reduced more than 50%.

The sequence of operations is given in Fig. 13. The air – natural gas torches at stations 4, 5 and 6 were adjusted to produce neutral or slightly reducing flames. Filler metal was BAg-1 in flux-paste form.

The completed assemblies were leak tested with air at 60 psi. Rejection rate was 1%, which was considered satisfactory. The joints were clean and ductile.

Joint Design. For the more widely used silver alloy and copper-zinc alloy filler metals, diametral clearances of 0.002 to 0.005 in. are suitable. For the BCuP filler metals, diametral clearances differ; clearances of 0.001 to 0.003 in. are suitable for BCuP-2 and BCuP-4, and 0.001 to 0.005 in. for BCuP-5.

Much torch brazing is done by face feeding of filler metal, and when this is desired, joints should be limited to a depth that can be quickly and adequately fed by the form of filler metal used. Deep joints and those that

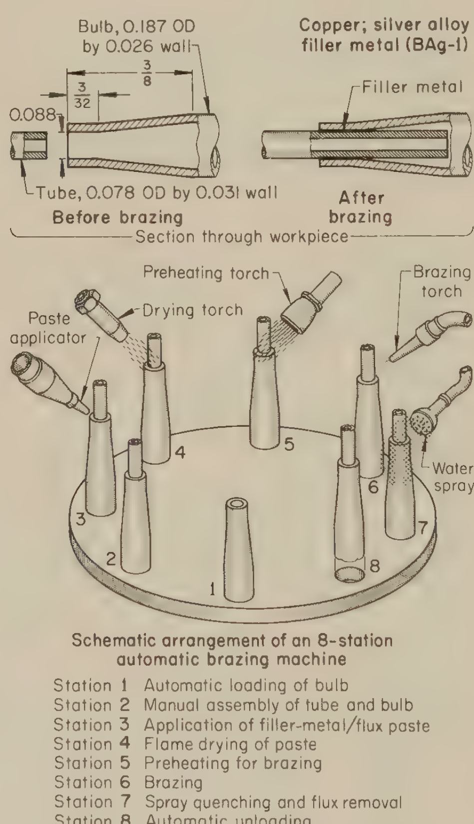


Fig. 13. Bulb-and-tube assembly brazed by mechanically held torches on an eight-station turntable (Example 646)

change direction sharply will require the use of preplaced filler metal.

The following example involves a type of failure that was corrected by changing from a corner joint that placed the braze in tension, due to bending, to a lap joint that placed the braze in shear and enlarged the area of contact of the joint.

Example 647. Change in Joint Design That Eliminated Failures Due to Leakage (Fig. 14)

The torch brazed assembly shown in Fig. 14 was the heat-dissipation section of a cooling unit for electronic equipment. Ethylene glycol solution circulated through the tubes and the water box. Freon vapor condensed on the outside surfaces of the tubes and tube fins (not shown in Fig. 14), dropping off as a liquid. All components shown were made of alloy 715 (copper nickel, 30%). The tube fins were made of copper, mechanically attached. The assembly was brazed with a manually operated oxy-natural gas torch, using BAg-2 filler metal.

The view at lower left and detail A in Fig. 14 show the joint between the water box and the cover as originally designed. A high percentage of these joints failed in service on the inside corner of the joint, due to tensile loading. Varying pressure loads imposed bending moments on the box walls, causing the joint to act like a hinge. The braze itself was far from perfect. Only about 1/16 in. of the joint depth was a true braze; the remainder had only the inherent strength of the silver alloy filler metal. Small defects nucleated leaks that caused loss of cooling and failure of the system.

To reduce stress concentrations, the cover plate was redesigned as a formed cup, which provided a lap joint that placed the braze in shear and increased the joint area considerably. The improved design of the cover assembly and the joint are shown in the lower middle view and detail B in Fig. 14. No field failures were reported for several thousand of the redesigned units.

Precision Torch Brazing. Although conventional torch brazing is capable of joining parts only a fraction of an inch in size, some small assemblies require the use of special equipment. When joining copper and copper alloy parts of this type, heat control is the principal difficulty, but other factors may be introduced. For instance, many electrical and electronic joints are not only small but are located close to components that can be functionally disabled by heat, spatter, and the removal of flux residues. If allowed to remain, an active flux will, in time, corrode the joint.

One method of meeting these problems is the use of a miniature oxy-hydrogen torch that utilizes a special gas generator. Torch tips are made from several sizes of hypodermic-needle tubing. Oxygen and hydrogen are generated by electrolysis of water, in the exact ratio required for complete combustion. (Alcohol vapor can be added to the fuel line to impart a blue cast to the otherwise less-visible flame.) This technique, when used with a self-fluxing BCuP-5-clad brazing sheet, proved advantageous in joining copper leads, as described in the next example.

Example 648. Technique for Brazing 0.008-In.-Diam Wires to 0.010-In.-Thick Terminals (Fig. 15)

Terminals to be attached to 0.008-in.-diam wire leads, as shown in Fig. 15, were made of a 0.004-in.-thick core of copper clad on both sides with 0.003-in.-thick layers of BCuP-5 brazing filler metal. At first,

several experimental assemblies were made by gas tungsten-arc welding. This method was unsatisfactory because the heat could not be controlled. Arc starts occurred in a burst that made observation by the operator difficult.

Actual production joints were made initially by capacitor-discharge resistance brazing. Expulsion from the joint caused spatter to be lodged on surfaces or concealed in crevices, where it changed the electrical properties of the device by induction or short circuiting. Inspection of the joint was difficult and time consuming, and repair time was excessive.

By changing to torch brazing, using a special oxy-hydrogen torch, the procedure was brought under control. Quality and reliability of the joint were greatly improved.

During the time when operators were learning to use this process, production rates were lower than before. After approximately three months, operator skill increased to the point where production time was equal to or slightly less than with the resistance brazing process. An over-all saving in time was realized because rework for broken or improperly brazed joints was almost eliminated. Operators came to prefer this method of brazing because they were better able to monitor their own work; they knew immediately if the joint was acceptable because they could watch the melting of filler metal and the formation of the fillet. All work was observed under low-power magnification.

The procedure was to form the prestripped wire lead manually so it would lie flat on the terminal to which it was to be brazed (Fig. 15, upper view). Torch heat was then applied until the fillets were formed. The wire was held in position by tweezers or an orange stick.

The oxy-hydrogen gas supply was derived from electrolysis of water at the rate of 6 cu ft per hour. This was equal to a heat output of 3500 Btu per hour. A methyl alcohol booster was used to add a bluish cast to the flame to permit easier control by the operator. The torch tips were made from 0.009-in.-ID hypodermic-needle tubes. A flashback arrester was incorporated with each torch.

A schematic diagram of the gas generator and equipment components required for one brazing station are shown in the lower view in Fig. 15. Cost for one generator and torch was $525. Production rate was 35 to 40 joints per hour for forming, assembly and brazing. As many as eight brazing stations could be operated from one generator.

Quality was verified by 100% operator inspection of the joints as they were made.

Induction Brazing

The efficiency of heating by induction for any purpose varies directly with the electrical resistivity of the alloy. Brass, because it has higher electrical resistivity, can be heated more efficiently than copper; steel, which has even higher resistivity, can be heated more efficiently than brass. In terms of the high-frequency power input and the time required to heat one pound of metal in a joint assembly to a brazing temperature of about 1300 F, a power input of 15 kw (at 450 kHz) will heat a steel joint to this temperature in about 16 seconds, whereas brass will require about 30 seconds, and copper about 55 seconds (Fig. 16).

Advantages. The general advantages of induction brazing (see page 631) are applicable to copper and its alloys.

In several examples in this section, the localized heating obtainable with induction brazing was advantageous. In the next example, induction brazing minimized warpage and postbraze cleaning, and required less operator skill than would have been needed for torch brazing.

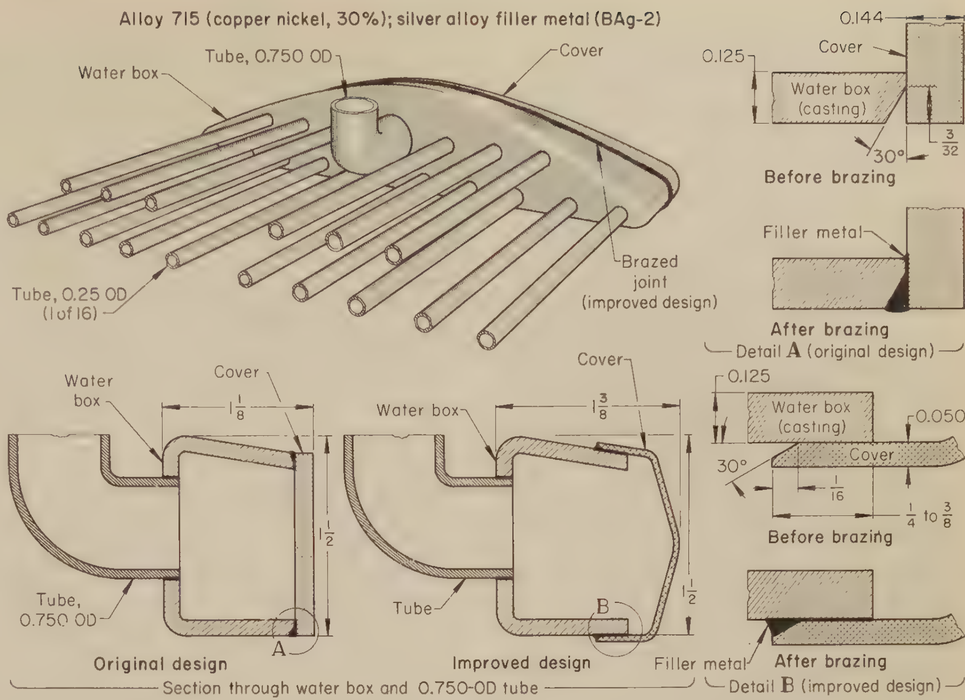


Fig. 14. Change in joint design that eliminated leakage in a torch brazed component of a cooler for an electronic system (Example 647)

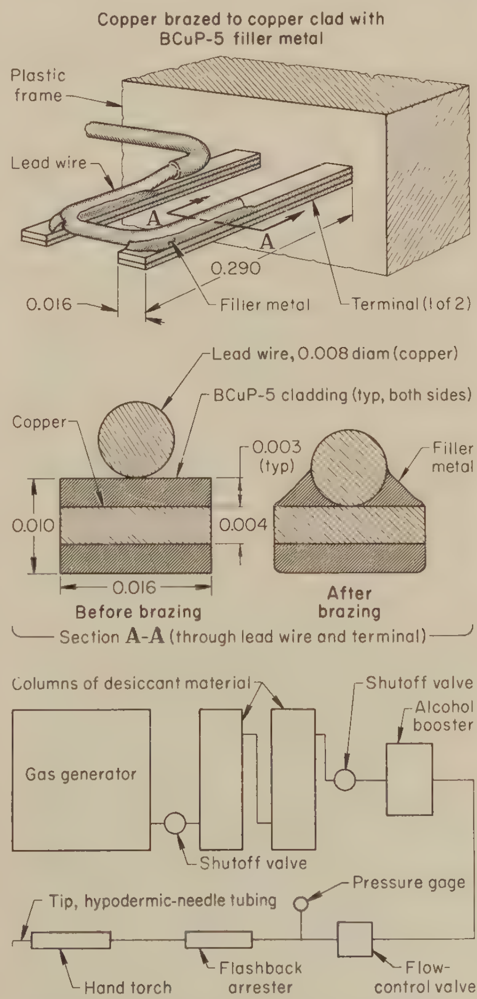


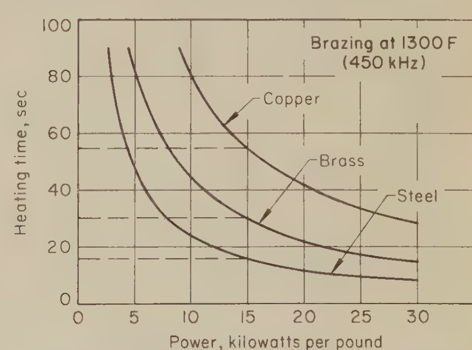
Fig. 15. Assembly of a lead wire and terminals that was brazed with a special oxy-hydrogen torch and self-fluxing filler metal, sectional views of the joint, and schematic of equipment layout (Example 648)

Example 649. Use of Induction Brazing To Minimize Warpage and Postbraze Cleaning (Fig. 17)

Alloy 110 (ETP copper) tubes ¾ in. in outside diameter were induction brazed to hot-water-tank covers, formed from alloy 230 (red brass, 85%), using the setup shown in Fig. 17. The resulting joints had to be leaktight at a pressure of 300 psi.

As shown in Fig. 17, the holding fixture, which was made of cemented-asbestos board, had a retaining shoulder at the edge and a stop at the center to support the pipe. The fixture was raised and lowered manually on a rack to move the joint into and out of the inductor.

Tubes and covers were degreased in trichlorethylene and bright dipped before being assembled for brazing. The joint surfaces were brushed with flux before the parts were assembled. A preformed ring of 0.050-in.-diam BCuP-5 filler-metal wire was placed over the tube, as shown in detail A in Fig. 17. The assembly was then raised to position in the single-turn inductor, where it was heated for 28 seconds, and then lowered and unloaded from the fixture.



Power is expressed as kilowatts required to heat one pound of metal at the joint to 1300 F. (SOURCE OF DATA: W. D. Wilkinson, *British Welding Journal*, Oct 1965)

Fig. 16. Power input and heating time required for high-frequency induction brazing of steel, brass and unalloyed copper

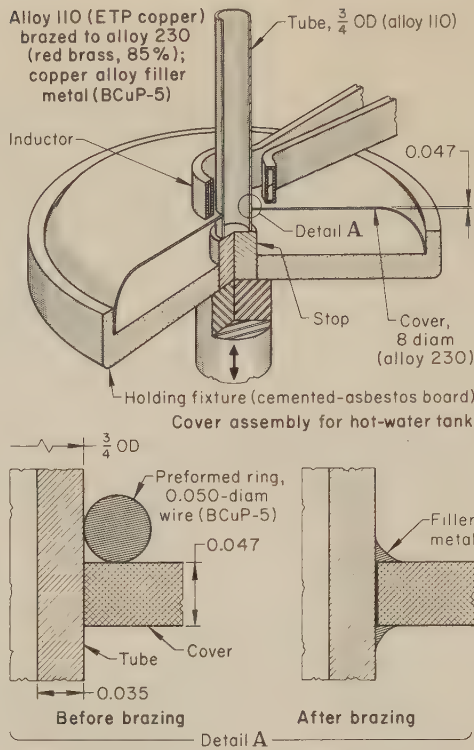
Selection of induction heating for this application was based primarily on the ability of the process to localize heat in the joint region, and thereby to minimize warpage and postbraze cleaning. The same assembly could have been brazed with a torch, but induction brazing provided for programed heat input and made possible the use of an operator with less skill than would have been required for torch brazing. Additional brazing conditions for the hot-water-tank assembly are given in the table accompanying Fig. 17.

Limitations. One of the general limitations of induction brazing is the cost of induction heating equipment, which far exceeds the cost of torch brazing equipment and usually exceeds the cost of equipment for resistance brazing or dip brazing in molten salt. Because efficiency in heating copper and copper alloys by induction is generally lower than that for heating steel (Fig. 16), the power requirements, and consequently the cost of the equipment for achieving a given production rate, are proportionately higher.

Other general limitations of induction brazing that relate to the size and shape of assemblies that can be brazed, the design of inductors, and requirements for matching impedances, apply to the brazing of copper and copper alloys as well as to the brazing of steel and are discussed in the article on Induction Brazing of Steel, beginning on page 631. Limitations that relate more specifically to the brazing of copper and copper alloys by induction include heating rate and the avoidance of overheating, both of which are less amenable to control in induction brazing than in furnace brazing or dip brazing in molten salt. Consequently, the induction brazing of copper alloys that are susceptible to hot cracking or to dezincification is more problematical. Other difficulties unique to induction brazing that may arise in connection with the use of a flux are discussed later in this section under "Use of Fluxes".

Power supplies used in the induction brazing of copper and copper alloys, including motor-generator sets, solid-state units, and vacuum-tube units, are discussed at length in the article on Induction Brazing of Steel. That article, which begins on page 631, also reviews the criteria for selection of frequency and the circuit requirements for matching impedances — factors that are closely related to the selection of a power supply.

Frequently, in the induction brazing of copper and copper alloys, it is necessary to maintain loose coupling between the inductor and the load (workpieces). Under conditions of loose coupling, there are two methods for improving heating efficiency. If a variable output transformer is used, an additional tuning capacitor may be connected directly across the inductor to increase inductor current. As an alternative, a high-impedance output circuit, designed specifically for brazing nonferrous metals, may be employed. This circuit does not include a variable output transformer; rather, it is designed so that the inductor is an actual part of the tank circuit inductance, with a relatively high voltage and current in the work circuit.



Conditions for Induction Brazing

Power supply	Vacuum-tube unit, 10 kw, 450 kHz
Inductor	Single-turn
Filler metal	BCuP-5 wire, 0.050-in. diam, preformed to ¾-in.-ID ring
Flux	Type 3A (AMS 3410D)
Brazing time	28 sec per joint
Production rate	60 joints per hour

Fig. 17. Tank-cover assembly that was brazed by induction to minimize warpage and postbraze cleaning (Example 649)

Design of Inductors. Guidance in the design of inductors is presented in the article on Induction Brazing of Steel, which begins on page 631 and contains numerous examples of single-turn and multiple-turn inductors used in brazing applications. Although the use of single-turn inductors is not uncommon in brazing copper and copper alloys (see Example 649), the efficiency in heating and, to some extent, the control of heating rate are greatly improved with the use of multiple-turn inductors. In the following example, the control of heat input and distribution was critical, and excellent results were obtained at a relatively low operating frequency (10 kHz) using a three-turn inductor.

Example 650. Use of a Multiple-Turn Inductor To Control Heat Input and Minimize Over-Aging of Chromium Copper (Fig. 18)

Chromium copper (0.6% Cr) has high electrical conductivity (78% IACS) and develops optimum mechanical properties in the precipitation-hardened condition. After solution heat treatment, it is aged at 750 to 930 F. Heating for brazing is critical because the copper will over-age or partly anneal at temperatures above 930 F, the over-aging effect increasing with increasing temperature and time at temperature.

Consequently, in brazing a tungsten–silver alloy contact to a precipitation-hardened chromium copper post (see Fig. 18), heat input to the post required careful control in order to minimize over-aging. It was required that the joint have high electrical conductivity and impact strength, and that the chromium copper post retain its hardness and strength to resist distortion when subjected to repeated impact. Brazing the tungsten–silver alloy contact required the use of a nickel-containing silver alloy filler metal for adequate wetting. BAg-3 was chosen in preference to BAg-4 or BAg-13 because BAg-3 has a lower brazing range (1270 to 1500 F); induction brazing was selected in order to control heat input and minimize the duration of the brazing cycle. Optimum control of heat input to the chromium copper post was obtained using the square three-turn inductor shown in Fig. 18.

Before brazing, the chromium copper base was bright dipped, and the tungsten–silver alloy contact was cleaned with an abrasive cloth. Type 3A flux paste was applied to both components with a brush. They were then assembled with a disk of filler metal placed between them, as shown in Fig. 18. Power supply was a 50-kw, 10-kHz motor-generator set. When the brazing alloy melted and flowed, the contact was rotated to release any entrapped gases and improve wetting. Production rate was ten joints per hour.

Inductors for Mass Production. Induction heating is well suited for the mass production of brazed assemblies, primarily because it is possible to design inductors that will heat an endless line of assemblies as they are carried into the induction field by conveyor belt or turntable. Hairpin and pancake inductors are most widely used for conveyorized applications, because they do not obstruct passage of the assemblies as they travel through the induction field; inductors for conveyorized setups are described on page 635 in the article on Induction Brazing of Steel.

Because steel assemblies heat more efficiently, they are generally more adaptable to brazing in a conveyorized setup than are assemblies made of copper and copper alloys. However, an alternative design for use with copper alloys, provided sufficient power is available, is the multiple-station inductor. With this type of inductor, two or more (often as many as six) assemblies can be brazed simultaneously or in a selective sequence that permits loading at one or more stations while other stations are heating.

Examples 651 and 652, which follow, describe respectively the application of a conveyorized setup and a multiple-station inductor to the brazing of copper and copper alloy assemblies at high production rates.

Example 651. Use of a Conveyorized Setup for Induction Brazing of Connector Assemblies (Fig. 19)

Small connector assemblies, consisting of two alloy 360 (free-cutting brass) studs and an alloy 172 (beryllium copper, 1.9%) spring clamp (see Fig. 19), were induction brazed on a 5-ft-long conveyor at a rate of 1900 assemblies per hour, using a modified pancake-type inductor and a 2½-kw, 300-kHz vacuum-tube power supply.

The brass studs, which had a tapered bore, were brazed to the platform of the spring clamp in the position shown in Fig. 19. The critical portions of the assembly that could not be overheated without causing serious damage were the thin (0.015-in.) wall at the top of the studs and the receptacle portion of the beryllium copper spring clamp, which was precipitation hardened prior to assembly for brazing. Heating, therefore, had to be largely restricted to the area of the joint without disrupting the preferred flow of filler metal or interfering with the seating of the studs on the clamp platform.

Proper heating was obtained with the modified pancake-type inductor shown in cross section at lower right in Fig. 19. The inductor, which was made of 3⁄16-in.-OD copper tubing, consisted of four active turns and a shorted central turn to which was soldered a plate with a pair of 6-in.-long copper intensifier shoes. The upper part of the gap between the shoes was tapered to direct energy toward the joint and away from the thin walls of the studs. At the inductor entrance, the gap between the shoes was 5⁄16 in.; from the midpoint of the inductor, the gap width flared to ½ in. at the inductor exit. The assemblies were held in place by inserting the receptacle end of the spring clamp into ceramic holders; the holders were located ½ in. apart, and traveled on the conveyor chain at a speed of 16 in. per minute.

Stud and clamp components were bright dipped prior to assembly. The studs were hopper-fed into clamping cavities in a rotary indexing table. A preform of BAg-1 strip 0.180 by 0.350 by 0.003 in. thick was pierced, cut off and placed automatically on each pair of studs. The beryllium copper spring clamp was placed on each assembly by hand. The ends of the studs were staked to the clamp to make the assembly self-jigging. The staked assemblies were dipped in a 20-to-1 solution of hot water and type 3A flux and air dried on a screen. Then the assemblies were placed, spring clamp down, into the ceramic holders, as shown at lower right in Fig. 19, and passed through the inductor. Time at temperature was approximately 22 seconds. After being brazed, the assemblies were washed in hot water.

Example 652. Use of Two Four-Station Inductors for High-Production Brazing of Motor Armatures (Fig. 20)

In the production of motor armatures, copper end rings were induction brazed to both ends of 14 copper rivets that held the armature laminations (see Fig. 20), at a rate of 433 assemblies per hour (two joints per assembly) in two four-station, single-turn inductors, using a 5-kw, 450 kHz vacuum-tube power supply. Induction brazing was selected for this application partly because the rapid rate of heating left the magnetic properties of the silicon steel armature laminations relatively unaffected.

Each of the eight inductor stations contained a graphite bushing into which an armature assembly could be placed. The inductors and bushings were attached to graphite blocks that supported the armatures during the brazing cycle.

Silver-containing filler metal BCuP-5 was selected for its suitable brazing range and because it is self-fluxing on copper. Because the filler metal would not wet the graphite holders, there was no difficulty in simultaneously brazing rings to both ends of the armatures. Conductivity was adequate.

Before brazing, the copper rings were degreased and bright dipped. Each inductor station was loaded by first placing a copper end ring at the bottom of the graphite bushing, followed by a preform of brazing alloy. The armature was then inserted in the hole in the graphite block (see Fig. 20, section A-A), and a second ring of filler metal was placed on top of the armature, followed by another end ring of copper. When one of the four-station inductors was loaded in this manner, power was applied and the brazing cycle began. The operator then began loading the second four-station inductor.

Use of Fluxes. The proximity of a moist or liquid flux to an uninsulated high-voltage, high-amperage inductor is often a source of difficulty unique to induction brazing. The difficulty increases with the tightness of coupling (the narrow distance across the air gap between inductor and workpiece) that is often required to heat copper and copper alloys efficiently.

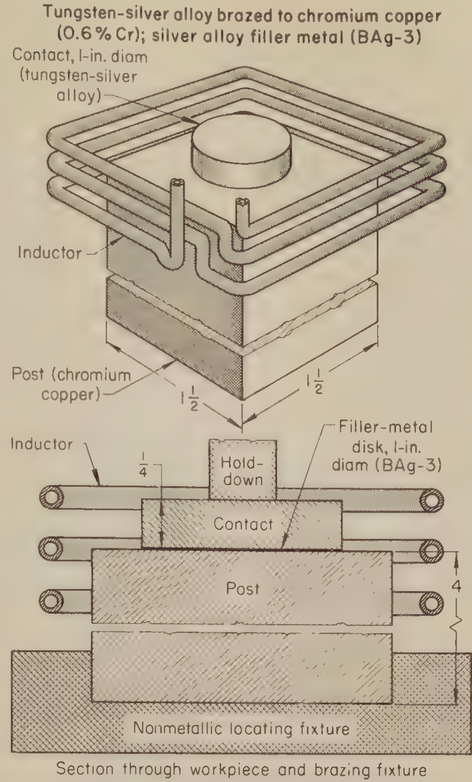


Fig. 18. Tungsten – silver alloy contact and chromium copper post in position for induction brazing, using a three-turn inductor (Example 650)

When the base metal heats, and the water in a moist flux is driven off in the form of steam, there is often a violent sputtering, followed by high-voltage arcing due to shorting between inductor and workpiece. If the arcing is of sufficiently high intensity, it will puncture the thin wall of the inductor tubing at one or more points, releasing a high-pressure spray of cooling water from the inductor. Damage to expensive inductors, fixtures and assemblies due to flux-induced arcing can be considerable. Although relatively uncommon, it is possible for a molten flux, by virtue of its electrical conductivity, to sputter when driven by field forces in a field of high intensity.

The hazard of arcing can be substantially reduced by protecting the inductor with an insulated cover, such as woven fiber-glass sleeving, by grounding the inductor, by allowing the water in moist fluxes to dry before they are heated, or by using a low-sputtering type of flux.

Avoiding the Use of Flux. In the earlier discussion of filler metals and in Example 652, it was noted that some filler metals, notably those in the BCuP series, have self-fluxing properties when used on commercial coppers. Because of their alloying constituents, however, most copper *alloys* require the use of a flux, even when BCuP filler metals are employed. Lead-containing alloys require the protective action of flux to prevent formation of a dross that will seriously impair wetting and the flow of filler metal.

In some applications, however, the use of a flux is unacceptable because of special service requirements or because flux residues cannot be removed completely after brazing. In the example that follows, copper plating served to eliminate the need for flux in induction brazing cartridge brass to a leaded commercial bronze.

Example 653. Avoiding the Use of Flux by Copper Plating the Copper Alloy Components (Fig. 21)

The reversing-valve assembly for an air conditioner, shown in Fig. 21, required leakproof brazed joints between the body, made from alloy 260 (cartridge brass, 70%) tubing, and the cover, made from alloy 314 (leaded commercial bronze).

Two specific restrictions were imposed in brazing one of the cover joints (Fig. 21, section A-A): (*a*) during brazing, a nylon needle located ½ in. away from the brazed joint could not be heated above 450 F; and (*b*) it was essential that the joint be brazed without the use of flux — not only to minimize the possibility of leakage, but also because it was not possible to clean the inside of the joint after it was brazed.

By heating the joint in 15 seconds and quenching it with water as soon as the filler metal solidified, heat was sufficiently localized so that the nylon needle was not overheated. By plating both the end of the body and the cover with a 0.0002-in. thick-

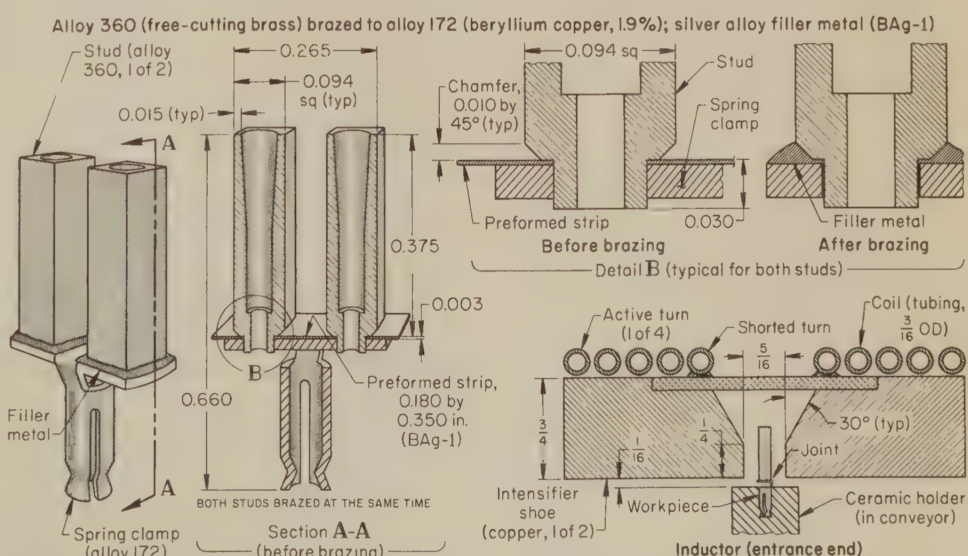


Fig. 19. Connector assembly and (at lower right) section through inductor used for conveyorized brazing (Example 651)

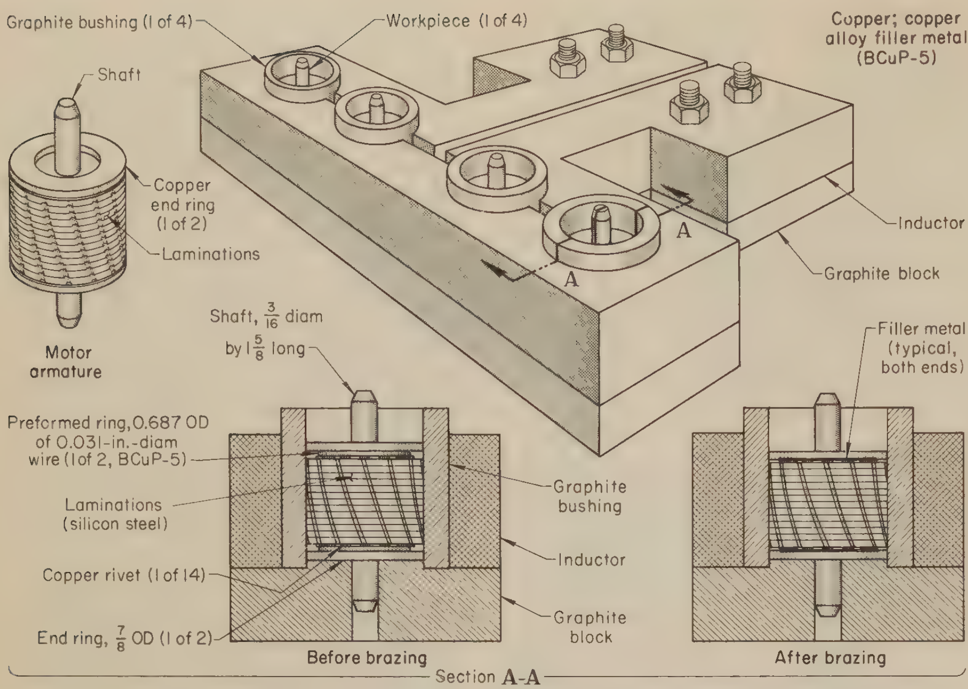


Fig. 20. Motor armature, and one of two four-station inductors used for high-production brazing of copper end rings to rivets holding armature laminations (Example 652)

ness of copper prior to brazing, leaktight joints were made without the use of flux.

The diametral clearance between the cover and the body was 0.002 to 0.010 in. When the two components were assembled, a preformed ring of BCuP-4 filler wire was pushed in place by hand, and then the end of the tube was crimped slightly, as shown in detail B in Fig. 21. Then the assembly was induction brazed, using a two-turn inductor (additional brazing conditions are given in the table with Fig. 21). Because of the short heating cycle (15 seconds), surfaces did not require postbraze cleaning and, following inspection, were immediately spray coated with black lacquer.

Joints were inspected 100% using a halogen-type leak detector that could detect leaks of the order of 10^{-5} standard cubic centimeters per second. The internal pressure at the time of testing was 400 psi. In addition, these assemblies were required to withstand 2600-psi internal pressure without rupture. The percentage of rejections due to leakage was extremely low (0.15%).

Cost of Brazing. The labor costs for induction brazing are usually lower than those for torch brazing, the process with which induction brazing is most often competitive. At high production rates, the total brazing cost per assembly generally favors induction brazing over torch brazing. However, the direct savings that accrue from the use of induction brazing will vary considerably among different plants because of differences in the time periods established for amortizing capital equipment. In the following example, the labor costs for brazing a bellows assembly by induction and by torch brazing are compared.

Example 654. Comparison of Labor Costs for Brazing a Bellows Assembly (Fig. 22)

Originally, torch brazing was used for joining the spring brass – gray iron bellows assembly shown in Fig. 22, at a production rate of 120 assemblies per hour. The chief advantage of torch brazing was low cost of equipment. Assemblies were prepared and brazed one at a time, requiring much skill and hand labor, at an hourly labor rate of \$3.60. Labor per assembly cost \$0.03.

To attain a higher production rate, induction brazing was substituted for torch brazing. The induction brazing setup consisted of two brazing fixtures, each of which accommodated four assemblies. Thus, one fixture was being loaded while the assemblies in the other fixture were being brazed. Less skill was needed to operate the induction brazing setup; hence the work could be done by personnel for whom the hourly rate was only \$2.16. At a production rate of 720 assemblies per hour (six times that of torch brazing), labor cost per assembly dropped to \$0.003.

Resistance Brazing

The chief use of resistance brazing is the joining of copper conductors, terminals and other parts in lap joints for electrical connections, where heating must be localized and closely controlled while brazing the joint, and the brazed joint must have low electrical resistance. Generation of heat in the filler metal and nearly complete filling with a thin layer of the filler metal in the joint help in meeting both of these objectives.

The filler metal most frequently used is BCuP-5, which in most applications is used without a flux when brazing copper. In spite of the comparatively low electrical conductivity of BCuP-5 (approximately 10% IACS, as shown in Table 1), there is no difficulty in producing brazed joints having a low voltage drop that is acceptable for nearly all applications, because the layer of filler metal in the brazed joint is very thin and because the joints are designed to provide a conducting contact region of larger area than the cross section of the smaller member.

Six examples of the production use of resistance brazing for making electrical connections on copper are presented in this article. The article on Resistance Brazing, pages 643 to 654, includes eight additional examples of resistance brazing of copper, and one (Example 602) in which the work metals were leaded brasses. Also included in that article are discussions of equipment, process applicability, electrodes, filler metals, fluxes, cleaning, joint design, and special techniques used.

Resistance brazing techniques described and illustrated by examples of practice in the remainder of the present article include brazing of multiple-strand copper wire, brazing of leads to commutator bars, brazing with portable machines and high-production resistance brazing.

Brazing of Multiple-Strand Copper Wire. Resistance brazing is the preferred brazing process for making connections of terminals or assemblies to stranded or braided copper electrical conductors. Torch brazing does not provide sufficiently localized or controlled heating for most applications of this type. Induction brazing, the only other brazing process that permits selective heating, provides well-controlled but somewhat less-localized heating than resistance brazing, and the equipment for induction brazing is more costly.

Resistance brazing, like other brazing processes, is often selected in preference to soldering, because of the higher strength of the filler metal.

The major arc welding processes usually are ruled out on the same basis as torch brazing; and arc processes that involve impact, such as stud and percussion welding, generally cannot be used because the stranded or braided copper conductors do not provide a rigid workpiece for the lap-type connections in common use (although T-joints of multiple-strand wires to flat surfaces have been made by percussion welding).

Resistance welding is not suitable for use on multiple-strand copper electrical conductors rated to carry a current higher than about 60 amp, because the amount of current needed to make the weld is prohibitively large. Such connections are made by resistance brazing using the "solidified joint" technique, as described in Examples 605 and 606.

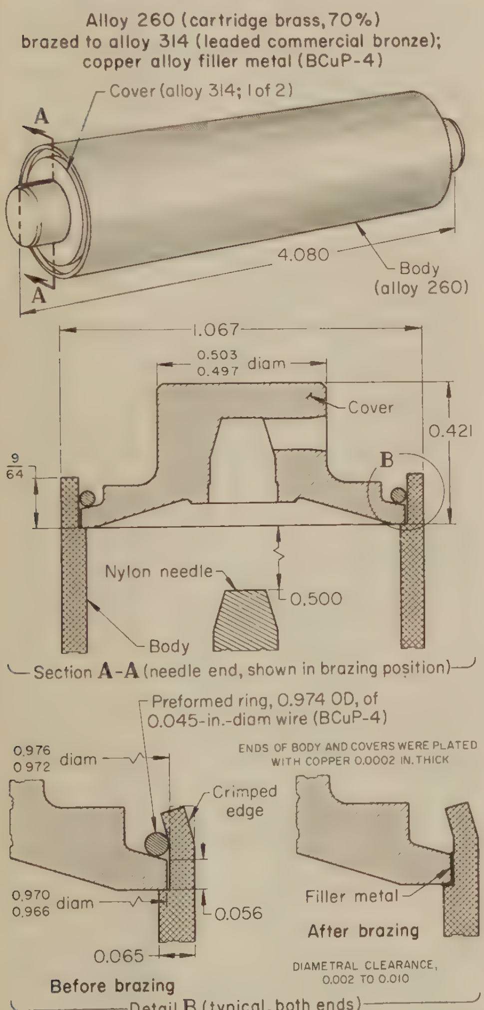
Connections to smaller multiple-strand conductors are made by either resistance welding or resistance brazing. Resistance welding has the advantage of requiring no filler metal, and is often faster than resistance brazing, as in Example 420. However, especially when the individual strands are small in diameter, it is difficult to prevent melting of strands in resistance welding. Resistance welding of a seven-strand silver-plated copper wire (strand diameter, 0.016 in.) to a coin silver (90 Ag, 10 Cu) ring in Example 422 depended on the beginning of melting at the silver-copper eutectic temperature (1436 F) and on carefully developed electrode design and operating conditions.

In the example that follows, resistance brazing was selected instead of resistance welding to join a 19-strand silver-plated copper wire (strand diameter, 0.014 in.) to a copper ring (instead of a silver alloy ring as in Example 422) in a similar arrangement, because the separate strands were melted by resistance welding of this smaller strand size.

The use of BCuP-5 filler metal in the resistance brazing procedure enabled melting to begin at a temperature of 1190 F and provided enough molten metal for effective heat transfer within the multiple-strand wire and from the wire to the copper ring, so that the strands did not overheat. The original joining procedure, based on manual tin-lead soldering, had been too slow and had produced joints of inconsistent quality, with excessive spreading of the solder.

Example 655. Use of Resistance Brazing in Preference to Soldering or to Resistance Welding, for Stranded Copper Wire (Fig. 23)

The electrical connection shown in Fig. 23 was originally made by manual soldering with a tin-lead alloy. Production rate was slow (about 60 connections per hour), the solder spread over an undesirably large

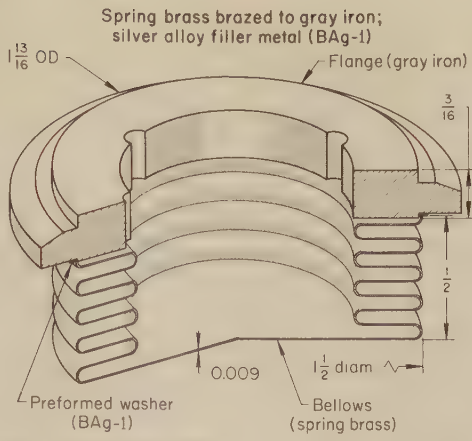


Conditions for Induction Brazing

Power supply	Vacuum-tube unit, 20 kw, 450 kHz
Inductor	Two-turn(a)
Fixture	For accurate centering and lengthwise positioning
Filler metal	BCuP-4, 0.045-in.-diam wire(b)
Flux	None
Heating time	15 seconds

(a) Made of 3/16-in.-OD copper tubing. Inside diameter of the inductor was 1 9/16 in. (b) Formed into a 0.974-in.-OD ring to fit the inside diameter of the body.

Fig. 21. Valve assembly that was induction brazed to avoid overheating the nylon needle, and selectively copper plated to avoid use of a flux (Example 653)



Item	Torch brazing(a)	Induction brazing(b)
Assemblies brazed per hour	120	720
Labor rate per hour	$3.60	$2.16
Labor cost per assembly	$0.03	$0.003

(a) The torch brazing data are based on a 30-second preparation and heating cycle, processing one assembly at a time. (b) In induction brazing, four assemblies were being brazed in a fixture while four additional assemblies were being loaded in a duplicate fixture.

Fig. 22. Compressor-seal bellows assembly joined at less cost by induction brazing than by torch brazing (Example 654)

area, and joint quality was unpredictable. Resistance welding was tried, but these attempts at directly fusing the 19-strand silver-plated copper wire to the copper ring failed because the temperature required to produce a bond invariably melted the thin (0.014-in.-diam) strands.

The method was changed to resistance brazing, using the setup illustrated in Fig. 23. The upper brazing electrode was made of RWMA class 14 material (molybdenum), and the lower electrode was made of RWMA class 2 material (chromium copper). As shown in the views at right in Fig. 23, the upper electrode had a 0.030-in.-deep groove with a 0.060-in. radius. This groove was wider than the wire and flattened it slightly when the electrodes closed. At the same time, the 0.030-in. depth was shallow enough to keep the electrode from touching the copper ring. The lower electrode was flat, so that it made line contact with the ring and concentrated the current flow and heating at the point of brazing.

The filler-metal preforms (wafers, 1/4 by 1/8 in., of 0.005-in.-thick BCuP-5) were manually placed at the bottom of the copper ring under the stranded wire.

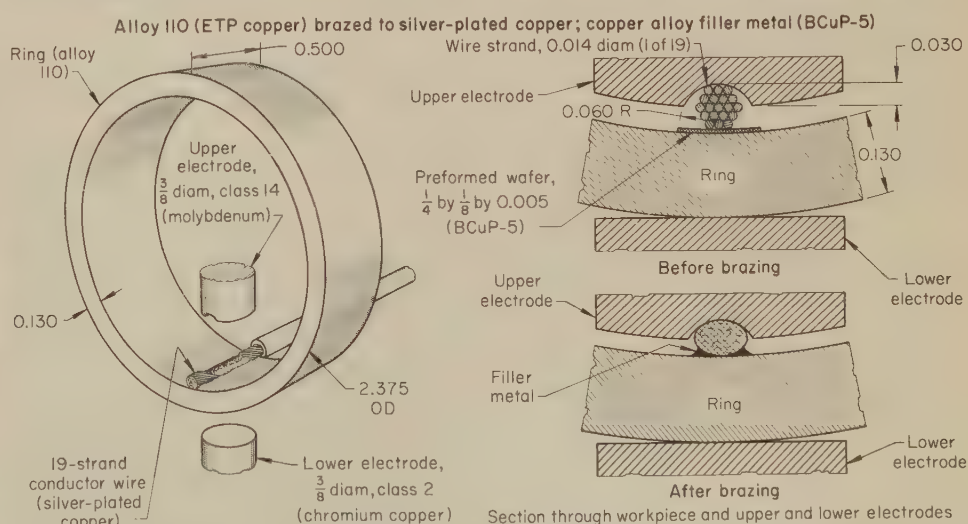
The ring (after degreasing) was placed on the bottom electrode with the filler metal directly above the contact point. A fiber support (not shown in Fig. 23) behind the electrode held the ring upright in brazing position. The end of the copper conductor wire was stripped of insulation and laid on the preform. No flux was used. The wire was hand held while the brazing cycle was initiated with a foot switch.

Additional brazing conditions are given in the table with Fig. 23.

Brazing of Leads to Commutator Bars. The suitability of resistance brazing for joining small copper electrical conductors to massive copper assemblies has led to the use of the process for attaching armature leads to commutator bars on large electrical motors and generators. Joints made by this method provide a large conducting cross section that prevents significant resistive heating at the connections in service. The joints are made at much lower temperature than would be possible by resistance welding, which could be done only with excessively high current and would also produce weaker joints and provide too small a conducting area at the joint.

The use of conventional resistance welding equipment and high-resistivity electrodes with specially contoured tips makes it possible to concentrate the heating at the joint, to keep the heating time to a minimum, and to obtain efficient handling and comparatively high production rates.

In the example that follows, resistance brazing replaced a slower and less

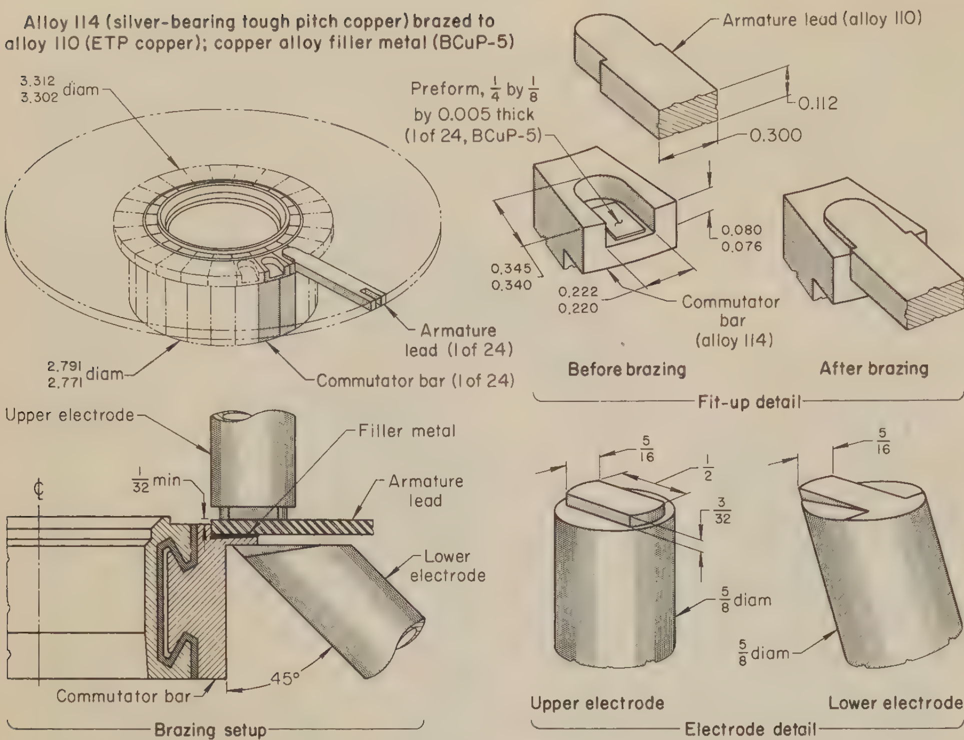


Conditions for Resistance Brazing

Machine	Press-type, air-operated, 10-kva resistance welding machine
Upper electrode	3/8-in.-diam RWMA class 14 (molybdenum)(a)
Lower electrode	3/8-in.-diam RWMA class 2 (chromium copper)(b)
Electrode force	150 lb
Filler metal	BCuP-5 preformed wafer(c)
Brazing current	80 amp
Voltage	3.7 v
Squeeze time	5 cycles
Heating time	17 cycles
Hold time	30 cycles
Production rate	180 assemblies per hour

(a) Contoured to a half circle, water-cooled. (b) Flat end, water-cooled. (c) Flux not used.

Fig. 23. Multiple-strand electrical-conductor wire and a copper ring that were joined by resistance brazing in preference to soldering or resistance welding (Example 655)



Conditions for Resistance Brazing

Machine	Press-type, air-operated 75-kva resistance welding machine	Filler metal	BCuP-5 preform, ¼ by ⅛ in., by 0.005 in. thick(a)
Electrodes	RWMA class 14 (molybdenum), water-cooled	Squeeze time	70 cycles
Electrode force	500 lb	Heating time	114 cycles(b)
Current	55 amp	Hold time	18 cycles
Voltage	1.5 v	Off time, minimum	120 cycles
		Brazing time, per joint	8 seconds

(a) Flux not used. (b) Six pulses, each of 11 cycles heating time plus 8 cycles cooling time.

Fig. 24. Assembly of armature leads to commutator bars, and setup for resistance brazing, which replaced staking and torch soldering, giving faster production and eliminating contamination and excessive annealing (Example 656)

satisfactory mechanical staking and torch soldering procedure that also produced unwanted heating effects.

Example 656. Resistance Brazing Instead of Torch Soldering for Lap-Joint Attachment of Armature Leads to Commutator Bars (Fig. 24)

The original method of making the commutator shown in Fig. 24 was to insert the alloy 110 armature leads into holes in the alloy 114 commutator bars, mechanically stake them, and finally solder with a tin-lead alloy. Joints were heated for soldering with a gas torch. Disadvantages of this method included slow production rate (30 seconds' soldering time per piece), contamination of working surfaces with solder and flux, and excessive annealing of the commutator bars under the slow heating with the torch.

The joint design was changed to the lap-type design shown in Fig. 24, in which flat copper armature leads were inserted in milled slots in the commutator bars and resistance brazed in place using BCuP-5 filler-metal preforms. With this filler metal no flux was required and, since filler metal did not bleed out of the joint, no postbraze cleaning was necessary. Before brazing, the leads were degreased in trichlorethylene. Because the slots were milled (without using a lubricant) just before brazing, no cleaning was necessary on the commutator bars.

Additional brazing conditions are given in the table with Fig. 24. By changing to the resistance brazing method, the time for making a connection was reduced by 73% (from 30 to 8 seconds).

In the next example, joint quality, localization and control of heat input, and initial cost of equipment were major factors in the selection of resistance brazing for attaching dual armature leads to commutator bars.

Example 657. Resistance Brazing Instead of Carbon-Arc Brazing for Joining Armature Leads to Commutators (Fig. 25)

When carbon-arc brazing was used for joining alloy 102 armature leads to alloy 110 commutator bars (see Fig. 25), the joints were porous and high in electrical resistance. This caused excessive temperature rise in the motors in which they were used.

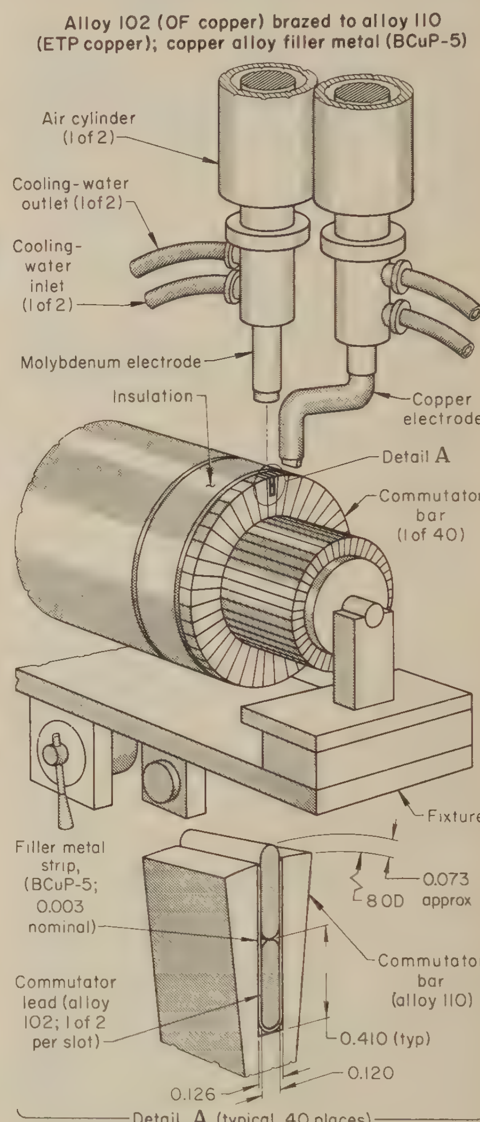
Changing the method of making the connections to resistance brazing, using BCuP-5 filler metal and the conditions listed with Fig. 25, eliminated the porosity and reduced the electrical resistance across the joint. A temperature of 1300 to 1350 F was required to ensure an acceptable joint. Torch brazing was ruled out because of excessive width of heating and inadequate heat control. Induction heating was rejected because the initial investment for equipment would have been too great.

The equipment included a 50-kva transformer with a 220-volt primary and taps on the secondary at 3.2, 3.8, 4.4 and 5.0 volts. As indicated in Fig. 25, the electrodes were air-operated and water-cooled.

The setup used for resistance brazing is shown in Fig. 25. The width of the slots in the riser portions of the commutator bars was increased by 0.006 in. to accommodate a U-shape strip of filler metal. Detail A in Fig. 25 shows the work arranged for brazing with the upper lead extending about 0.073 in. above the commutator bar, to be contacted by the molybdenum electrode. Neither fluxing nor prebraze cleaning was required.

To initiate the brazing sequence, a valve was manually actuated, and the air cylinders positioned and applied pressure to the electrodes. The contactor switch was then activated by a push button to energize the primary of the transformer. High secondary current heated the commutator bar in the area between the electrode tips (a red color was visible, starting at the tips and progressing to a point between them). The filler metal melted, the leads in the slot partially melted, and the leads were compressed approximately flush with the bar surface. Use of a controlled amount of filler metal made final grinding unnecessary.

Visual observation by the operator permitted him to terminate the heating sequence



Conditions for Resistance Brazing

Machine	Press-type, air-operated 50-kva resistance welding machine
Electrodes contacting commutator bar	RWMA class 1 (cadmium copper)
Electrodes contacting armature lead	RWMA class 14 (molybdenum)
Electrode force	80 lb(a)
Voltage	5.0 v(a)
Filler metal	BCuP-5, 0.003-in.-thick strip
Flux	None
Production per hour	Four commutators(b)

(a) Squeeze time, 10 sec; five heating pulses, each 2 sec long. (b) Forty-slot commutators.

Fig. 25. Arrangement for resistance brazing pairs of armature leads to commutator bars, to avoid porosity that was experienced when carbon-arc brazing was used (Example 657)

as soon as the leads in the commutator slot reseated themselves. The transformer circuit was then opened by a push button and cooling began. The electrodes were then retracted by releasing the air valve.

As a safety measure, a timer in the circuit limited brazing time to a maximum of 1 min. If required time exceeded this setting, the operator had to release and repush the operating button.

Brazing With Portable Machines. One common use of portable resistance welding machines for resistance brazing is attaching bus-bar terminals or similar strip-type connectors to large electrical equipment that cannot be brought to, or positioned for brazing in, a conventional fixed-position resistance welding machine.

Electrical connections to such equipment can often be made more economically by resistance brazing than by mechanical means, and are made more readily by resistance brazing than by arc welding.

In the example that follows, the selection of electrode material was important for successful results in resistance brazing strip-type copper bridging connectors to a large electrical apparatus, and cost was less than for making swaged or crimped connections using braided conductors.

Example 658. Use of a Portable Machine for Resistance Brazing of Strip-Type Connectors to Large Electrical Apparatus (Fig. 26)

The joints shown in Fig. 26 for the bridging connectors on electrical equipment were originally made using crimped swage connectors. Cost was high: $0.15 to $0.45 per joint, depending on the kva rating. Braided copper leads had to be used with this type of joint. On some equipment, connections were made at high cost by bolting.

The joint design was changed to that shown in Fig. 26, using strip-type connectors 0.040 in. thick by 1 in. wide. (Similar joints, not shown in Fig. 26, were also made in the same way using connectors 0.080 in. thick by 2 in. wide.) With the revised joint design, gas tungsten-arc welding was tried, but it was impossible to produce fusion over a sufficiently large area to provide adequate current-carrying capacity across the joint.

The next attempt, using the revised joint design, was resistance brazing using carbon electrodes, but excessive heat was generated at each brazed joint, with the extent of overheating depending on the condition of the carbon electrodes. Molybdenum-faced electrodes were substituted, and joints resistance brazed using BCuP-5 filler metal were made economically and with minimum damage to the electrical insulation near the joint.

Production rate and unit labor cost were approximately the same as for the mechanical joint, but the cost per joint of $0.005 for filler metal resulted in a substantial saving, as compared to the original material cost of $0.15 to $0.45 for a swage connector. Rejection rate for joints made by the resistance brazing method was less than 0.5%, and defects were repairable.

Additional data on equipment, operating conditions and results are given in the table accompanying Fig. 26.

Resistance brazing done with portable resistance welding machines is a convenient and economical way of interconnecting large copper electrical bus bars or of attaching either large or small copper bus bars to motor-generators, transformers and other electrical equipment. Lap joints made in this way have a bonding area that provides adequate strength and current-carrying capacity. Joints that have a large area of contact are brazed by making a series of spot brazes that overlap to provide full-joint or nearly full-joint bonding.

The low melting temperature of the filler metal helps to avoid overheating and excessive annealing of the work, and the usual selection of self-fluxing BCuP-5 alloy for the filler metal avoids corrosion problems and the need for flux removal.

In the example that follows, production time was cut in half and waste of filler metal was eliminated by changing from torch brazing to portable-machine, multiple-spot resistance brazing, for making a bus-bar connection of large area.

Example 659. Resistance Brazing Instead of Torch Brazing for a 32-Sq-In. Lap Joint on Bus Bar (Fig. 27)

The bus bar and strip assembly shown in Fig. 27 served as a terminal for a transformer. Originally the two alloy 110 components were joined by torch brazing using a filler metal of the BAg series. Torch brazing required the operator to use both hands — one to hold the torch and the other to feed the filler metal. Consequently, it was necessary to clamp the assemblies for brazing. In addition, some of the silver alloy filler metal was wasted by dropping on the floor.

By the improved method, the components were joined by multiple-spot resistance brazing in a portable resistance welding machine, using a 4-by-8-in. preformed strip of 0.005-in.-thick BCuP-5 filler metal between the bus bar and strip, as shown in Fig. 27. This method reduced production time by 50%, and eliminated waste of filler metal and the need for clamping.

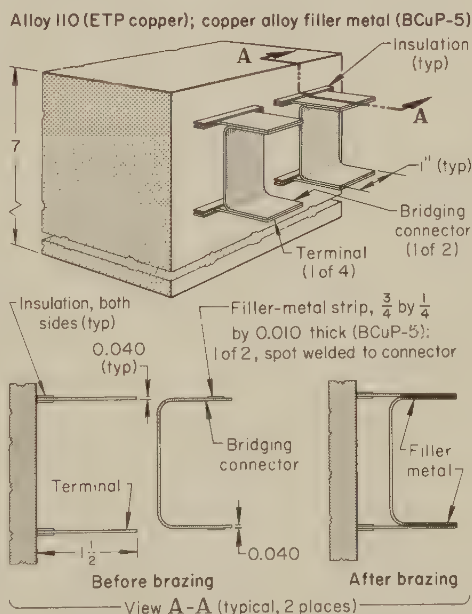
The material being joined was received in good condition and no precleaning was necessary. Also, since no flux was required with BCuP-5, no cleaning after brazing was needed. Brazing was done with a 22-kva machine equipped with manually operated water-cooled tongs having carbon-graphite electrodes. The area of each electrode face was approximately 1 sq in. Current was controlled by the operator with a foot switch. Maximum current flow was 2000 amp.

The filler metal was melted at each braze spot in an area larger than that of the electrode, providing bonding on 80% or more of the total joint area.

The same general technique was used for resistance brazing similar transformer terminals consisting of components smaller than those shown in Fig. 27.

In making the smallest connections of this type, in which ½-in. by 0.012-in. by 2½-in.-long copper bus bar was joined to copper strip 1¾ in. wide by 0.010 in. thick, ⅜-in.-diam copper-coated carbon-graphite electrodes were used with tongs that were not water-cooled. Thus, joint area was from 32 sq in. for the largest size to 0.88 sq in. for the smallest size.

High-Production Resistance Brazing. Production rates approaching those obtained in mass-production resistance welding are achieved in resistance brazing of some high-volume small copper parts, in spite of the need for an added operation to place filler metal (and, sometimes, flux) in the joint (see the section "Resistance Brazing as a High-Production Process" on page 650 in the article on Resist-

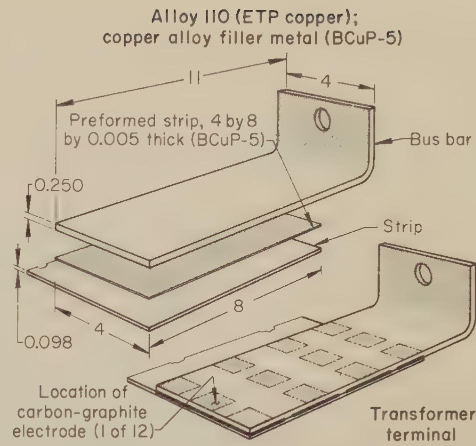


Conditions for Resistance Brazing

Machine	Portable resistance welding machine with internal cooling system
Electrodes	RWMA class 1 (cadmium copper), with RWMA class 14 (molybdenum) facing
Filler metal	BCuP-5, preformed strip, ¾ by ¼ in., by 0.010 in. thick
Flux	None
Production per hour	15 two-joint assemblies
Annual production	50,000 assemblies
Rejection rate	Less than 0.5%
Filler-metal cost per joint	$0.005
Savings per joint(a)	$0.145 to $0.445

(a) Compared with cost of swage connector used in original mechanical joining method

Fig. 26. Joints of strip-type bridging connectors to large electric apparatus made by resistance brazing, using a portable machine, at lower cost than original mechanical joints of braided connectors (Example 658)



Conditions for Resistance Brazing

Machine	Portable 22-kva resistance welding machine with manual, water-cooled tongs
Fixtures	None
Electrodes	Carbon-graphite, 1 in. square
Electrode force	Hand pressure by operator
Filler metal	BCuP-5 strip (see drawing)
Flux	None
Brazing current	2000 amp (max)
Heating time	Controlled manually by observation of filler-metal flow
Joint area	32 sq in.
Number of braze spots	12(a)

(a) The filler metal was melted at each braze spot in an area larger than the electrode area, thus providing bonding on 80% or more of the total joint area.

Fig. 27. Transformer terminal that was assembled by manual multiple-spot resistance brazing using carbon-graphite electrodes, instead of the original torch brazing procedure (Example 659)

ance Brazing). When resistance brazing copper parts in large quantities, the self-fluxing filler metal BCuP-5 is usually selected, so that there is no need to add flux before brazing and to remove flux residues afterward.

In some applications, filler metal for resistance brazing can be provided in the form of a suitable coating already present on one or both members to be joined, thus eliminating not only the use of flux but also the operation of placing filler metal at the joint. This was done in Example 603, in which copper wire was joined by high-speed resistance brazing to copper terminals clad with BCuP-5 filler metal.

In the example that follows, a critical feature was complete removal of oxide from a high-carbon steel spring before electroplating it with copper and silver. The plating served as filler metal for resistance brazing a braided copper wire to the steel spring.

Example 660. Mass-Production Resistance Brazing of Braided Copper Wire to a High-Carbon Steel Spring Electroplated With Copper and Silver (Fig. 28)

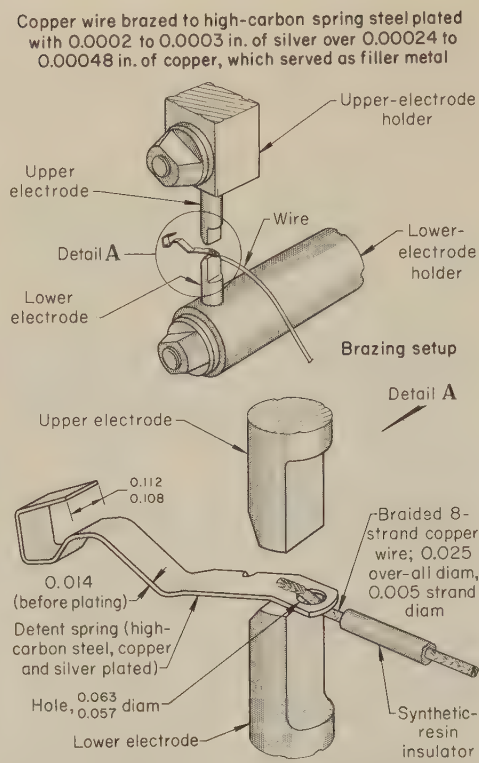
The detent-spring assembly shown in Fig. 28 was resistance brazed in mass production with the aid of plated-on filler metal on the steel spring (a copper plate 0.00024 to 0.00048 in. thick and an overlay of silver plate 0.0002 to 0.0003 in. thick). When heat was applied, a relatively low-melting copper-silver alloy was formed that provided sufficient filler metal to permit joining the stranded copper wire to the steel spring without significant fusion of the base metals. This assembly was resistance brazed at a production rate of 927 pieces per hour for use in an electric shaver.

Rejection rate at first was excessive in resistance brazing this assembly, because of frequent failure of the wire to adhere to the spring after brazing. In many instances, broken strands of wire exceeded the permissible 10% of the total strands. An examination of the resistance welding machine showed that it was functioning properly and that settings and electrode materials were correct for the production of sound joints.

The copper conductor wire was 0.025 in. in over-all diameter and of stranded construction. The spring was 0.014-in.-thick high-carbon steel (0.70 to 0.80% C) with silver plating over a copper underplate, as described above. Examination of the spring showed that a heavy oxide layer was present on the steel surface underneath the plating. When the oxide coating was removed before electroplating, the wire and spring could be brazed together satisfactorily. Proper control of the protective atmosphere while hardening and tempering the spring to Rockwell C 45 to 49 prevented the formation of the interfering oxide layer.

At the same time, it was determined in tests that braided wire suffered fewer broken strands during brazing than did stranded wire. Therefore, a change was made to 8-strand braided wire with 20 to 30 picks per inch. This wire had an over-all diameter (excluding insulation) of 0.025 in. and a strand diameter of 0.005 in.

After these changes were made, acceptable joints were produced with high reliability at an over-all production rate of 927 joints per hour. Joints had to withstand a force of 1 lb in a pull test. Frequency of sampling for the pull test was two assemblies from each 75. Additional brazing conditions are given in the table with Fig. 28.



Conditions for Resistance Brazing

Machine	Semiautomatic, air-operated resistance welding machine
Power supply	Capacitor bank, 1.5 kva(a)
Electrode material	RWMA class 13 (tungsten)
Filler metal	Copper plus silver, electroplated
Flux	None
Electrode force	8 lb
Production rate	927 joints per hour

(a) Capacitance settings for 50, 100 or 200 mfd

Fig. 28. Setup for high-speed resistance brazing of stranded wire to a detent spring for an electrical switch, in which electroplated coatings of copper and silver served as filler metal (Example 660)

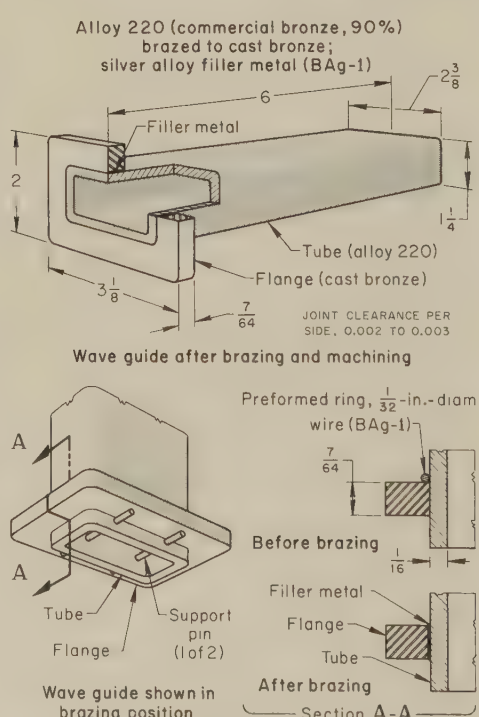


Fig. 29. Wave-guide assembly that was brazed by partial immersion in a molten salt bath (Example 661)

Dip Brazing

Salt bath furnaces used for the silver brazing of steel assemblies can be used also for silver brazing of copper and copper alloys. The same neutral salts, operating temperatures, and brazing procedures are used for dip brazing of most copper alloys as are used for steel (see the article on Dip Brazing of Steel in Molten Salt, which begins on page 655 in this volume).

Typical applications of dip brazing of copper alloys in molten salt are: wave guides and wave-guide hardware, flowmeter hardware, and capillary-tube-and-bellows assemblies.

The support given immersed workpieces by the buoyancy of the molten salt, and the rapid and even heating afforded by dip brazing, make this process especially suitable for joining assemblies that require minimum distortion, such as wave guides. When a wave-guide assembly has a large number of brazed joints, some external and some internal, a salt bath is particularly efficient for simultaneous brazing of all joints in a single immersion in the molten salt. With dip brazing, a flange fitting and the end of a wave-guide tube to be joined to it can be brazed by immersing only the joint portion in the molten salt bath, as in the example that follows.

Example 661. Use of Dip Brazing To Minimize Distortion (Fig. 29)

The wave-guide assembly shown in Fig. 29, which consisted of a straight tube of alloy 220 (commercial bronze, 90%) and a flange of cast bronze, was used in electronic equipment. It was required that the dimensions of the thin-wall tube (1¼ by 2⅜ in., by 1/16-in. wall) be maintained to close tolerances, and dip brazing was chosen as the joining process in order to avoid unacceptable amounts of warpage. (Torch brazing had been tried but resulted in excessive distortion.)

After any burrs were removed from the joint area, the tube and flange were degreased, bright dipped, rinsed in water, and dried. The parts were assembled so that the tube extended through the flange. Two accurately located sets of holes were drilled through the longer sides of the rectangular tube, and a pin was inserted through each set of holes to support the flange in the vertical position during brazing.

Filler metal in the form of a rectangular preform of 1/32-in.-diam BAg-1 wire was placed around the tube and adjacent to the flange (opposite the face). Type 3A flux was applied to the joint area, and the assembly was preheated in an oven to 600 F for 5 min to dry the flux and shorten the time required in the brazing bath.

For brazing, the assembly was supported vertically (flange down) on a rack, which was suspended from a rod extending through the tube. Supported in this manner, the assembly was self-jigged with gravity locating of the flange. (Self-jigging by staking was used on some similar wave-guide assemblies, and tack welding was used on others.)

Several assemblies simultaneously were partly immersed to a depth of about 3 in. for 1¼ min in a molten bath of neutral chloride salt (55% barium chloride, 25% sodium chloride, 20% potassium chloride) operated at 1350 F. After brazing, the assemblies were allowed to cool in air to approximately 500 to 600 F before they were washed in hot water to remove any residue of salt and flux, rinsed in hot water, bright dipped to remove slight oxidation that formed during cooling, rinsed in cold water, and dried.

Uniform fillets were formed and satisfactory joint penetration was obtained. The flange face was subsequently machined, which also removed a portion of the tube that extended beyond the flange. The final dimensions of the assembly were within tolerance.

Index

Numbered Alloys

A

The letter E, F, or T (in parentheses) following an index entry means that the information is in an Example, Figure, or Table, and the letter A following an entry means that the topic is the subject of an article.

C

D

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K

L

M

R

T

Some Abbreviations and Symbols Used in This Volume

α	angle
A	area
ac	alternating current
AISI	American Iron and Steel Institute
amp	ampere
AMS	Aerospace Materials Specification
ANSI	American National Standards Institute
approx	approximately
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
avg	average
AWS	American Welding Society
AWWA	American Water Works Association
bbl	barrel
Bé	Baumé
Bhn	Brinell hardness number
Btu	British thermal unit
C	Centigrade
cfh	cubic feet per hour
cm	centimeter
cps	cycles per second
cu	cubic
d	inside diameter
D	diameter; outside diameter
dc	direct current
dcrp	direct current, reverse polarity
dcsp	direct current, straight polarity
diam	diameter
est	estimated
ETP	electrolytic tough pitch (copper)
Ex.	Example
F	Fahrenheit
fpm	feet per minute
fps	feet per second
ft	foot
g	gram
gal	gallon
gpm	gallons per minute
$>$	greater than
h	height; depth
HF	high frequency
hp	horsepower
hr	hour
Hz	Hertz
IACS	International Annealed Copper Standard
ID	inside diameter
in.	inch
ipm	inches per minute
kHz	kiloHertz
kj	kilojoule
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	length
lb	pound
$<$	less than
ma	milliampere
max	maximum
MCM	thousand circular mils
mfd	microfarad
mg	milligram
microamp	microampere
micro-in.	micro-inch
microsec	microsecond
milliamp	milliampere
millisec	millisecond
min	minimum; minute
mm	millimeter
mod	modified
neg	negative (−)
NEMA	National Electric Manufacturers' Association
NFPA	National Fire Protective Association
No.	number
OC	on center
OD	outside diameter
oz	ounce
P	pressure
pc	piece
pH	hydrogen-ion concentration (acidity)
pos	positive (+)
ppm	parts per million
psi	pounds per square inch
psig	pounds per square inch gage
r	inside radius
R	radius; outside radius
R_B	Rockwell B scale
R_C	Rockwell C scale
rem	remainder
rpm	revolutions per minute
RWMA	Resistance Welder Manufacturers' Association
SAE	Society of Automotive Engineers
scf	standard cubic foot
sec	second
sfm	surface feet per minute
sq	square
t	stock thickness
temp	temperature
TIR	total indicator reading
typ	typical
UNC	Unified coarse thread
UNF	Unified fine thread
v	volt
vol	volume
w	watt
w	width
wt	weight

Geometric Characteristic Symbols

Characteristic	Symbol
Flatness	▱
Straightness	—
Roundness (circularity)	○
Cylindricity	⌭
Profile of any line	⌒
Profile of any surface	⌓
Parallelism	∥
Perpendicularity (squareness)	⊥
Angularity	∠
Runout	↗
True position	⊕
Concentricity	◎
Symmetry	⌯
Surface roughness, micro-in.	√

Temperature Conversions

The general arrangement of this table was devised by Sauveur and Boylston more than 40 years ago. The middle columns of figures (in **boldface** type) contain the readings (°F or °C) to be converted. If converting from degrees Fahrenheit to degrees Centigrade, read the Centigrade equivalent in the column headed "C". If converting from Centigrade to Fahrenheit, read the Fahrenheit equivalent in the column headed "F".

F		C	F		C	F		C	F		C	F		C
.....	−458	−272.22	.....	−308	−188.89	−252.4	−158	−105.56	+17.6	−8	−22.22	287.6	142	61.11
.....	−456	−271.11	.....	−306	−187.78	−248.8	−156	−104.44	+21.2	−6	−21.11	291.2	144	62.22
.....	−454	−270.00	.....	−304	−186.67	−245.2	−154	−103.33	+24.8	−4	−20.00	294.8	146	63.33
.....	−452	−268.89	.....	−302	−185.56	−241.6	−152	−102.22	+28.4	−2	−18.89	298.4	148	64.44
.....	−450	−267.78	.....	−300	−184.44	−238.0	−150	−101.11	+32.0	±0	−17.78	302.0	150	65.56
.....	−448	−266.67	.....	−298	−183.33	−234.4	−148	−100.00	+35.6	+2	−16.67	305.6	152	66.67
.....	−446	−265.56	.....	−296	−182.22	−230.8	−146	−98.89	+39.2	+4	−15.56	309.2	154	67.78
.....	−444	−264.44	.....	−294	−181.11	−227.2	−144	−97.78	+42.8	+6	−14.44	312.8	156	68.89
.....	−442	−263.33	.....	−292	−180.00	−223.6	−142	−96.67	+46.4	+8	−13.33	316.4	158	70.00
.....	−440	−262.22	.....	−290	−178.89	−220.0	−140	−95.56	+50.0	+10	−12.22	320.0	160	71.11
.....	−438	−261.11	.....	−288	−177.78	−216.4	−138	−94.44	+53.6	+12	−11.11	323.6	162	72.22
.....	−436	−260.00	.....	−286	−176.67	−212.8	−136	−93.33	+57.2	+14	−10.00	327.2	164	73.33
.....	−434	−258.89	.....	−284	−175.56	−209.2	−134	−92.22	+60.8	+16	−8.89	330.8	166	74.44
.....	−432	−257.78	.....	−282	−174.44	−205.6	−132	−91.11	+64.4	+18	−7.78	334.4	168	75.56
.....	−430	−256.67	.....	−280	−173.33	−202.0	−130	−90.00	+68.0	+20	−6.67	338.0	170	76.67
.....	−428	−255.56	.....	−278	−172.22	−198.4	−128	−88.89	+71.6	+22	−5.56	341.6	172	77.78
.....	−426	−254.44	.....	−276	−171.11	−194.8	−126	−87.78	+75.2	+24	−4.44	345.2	174	78.89
.....	−424	−253.33	.....	−274	−170.00	−191.2	−124	−86.67	+78.8	+26	−3.33	348.8	176	80.00
.....	−422	−252.22	−457.6	−272	−168.89	−187.6	−122	−85.56	+82.4	+28	−2.22	352.4	178	81.11
.....	−420	−251.11	−454.0	−270	−167.78	−184.0	−120	−84.44	+86.0	+30	−1.11	356.0	180	82.22
.....	−418	−250.00	−450.4	−268	−166.67	−180.4	−118	−83.33	+89.6	+32	±0.00	359.6	182	83.33
.....	−416	−248.89	−446.8	−266	−165.56	−176.8	−116	−82.22	+93.2	+34	+1.11	363.2	184	84.44
.....	−414	−247.78	−443.2	−264	−164.44	−173.2	−114	−81.11	+96.8	+36	+2.22	366.8	186	85.56
.....	−412	−246.67	−439.6	−262	−163.33	−169.6	−112	−80.00	+100.4	+38	+3.33	370.4	188	86.67
.....	−410	−245.56	−436.0	−260	−162.22	−166.0	−110	−78.89	+104.0	+40	+4.44	374.0	190	87.78
.....	−408	−244.44	−432.4	−258	−161.11	−162.4	−108	−77.78	107.6	42	5.56	377.6	192	88.89
.....	−406	−243.33	−428.8	−256	−160.00	−158.8	−106	−76.67	111.2	44	6.67	381.2	194	90.00
.....	−404	−242.22	−425.2	−254	−158.89	−155.2	−104	−75.56	114.8	46	7.78	384.8	196	91.11
.....	−402	−241.11	−421.6	−252	−157.78	−151.6	−102	−74.44	118.4	48	8.89	388.4	198	92.22
.....	−400	−240.00	−418.0	−250	−156.67	−148.0	−100	−73.33	122.0	50	10.00	392.0	200	93.33
.....	−398	−238.89	−414.4	−248	−155.56	−144.4	−98	−72.22	125.6	52	11.11	395.6	202	94.44
.....	−396	−237.78	−410.8	−246	−154.44	−140.8	−96	−71.11	129.2	54	12.22	399.2	204	95.56
.....	−394	−236.67	−407.2	−244	−153.33	−137.2	−94	−70.00	132.8	56	13.33	402.8	206	96.67
.....	−392	−235.56	−403.6	−242	−152.22	−133.6	−92	−68.89	136.4	58	14.44	406.4	208	97.78
.....	−390	−234.44	−400.0	−240	−151.11	−130.0	−90	−67.78	140.0	60	15.56	410.0	210	98.89
.....	−388	−233.33	−396.4	−238	−150.00	−126.4	−88	−66.67	143.6	62	16.67	413.6	212	100.00
.....	−386	−232.22	−392.8	−236	−148.89	−122.8	−86	−65.56	147.2	64	17.78	417.2	214	101.11
.....	−384	−231.11	−389.2	−234	−147.78	−119.2	−84	−64.44	150.8	66	18.89	420.8	216	102.22
.....	−382	−230.00	−385.6	−232	−146.67	−115.6	−82	−63.33	154.4	68	20.00	424.4	218	103.33
.....	−380	−228.89	−382.0	−230	−145.56	−112.0	−80	−62.22	158.0	70	21.11	428.0	220	104.44
.....	−378	−227.78	−378.4	−228	−144.44	−108.4	−78	−61.11	161.6	72	22.22	431.6	222	105.56
.....	−376	−226.67	−374.8	−226	−143.33	−104.8	−76	−60.00	165.2	74	23.33	435.2	224	106.67
.....	−374	−225.56	−371.2	−224	−142.22	−101.2	−74	−58.89	168.8	76	24.44	438.8	226	107.78
.....	−372	−224.44	−367.6	−222	−141.11	−97.6	−72	−57.78	172.4	78	25.56	442.4	228	108.89
.....	−370	−223.33	−364.0	−220	−140.00	−94.0	−70	−56.67	176.0	80	26.67	446.0	230	110.00
.....	−368	−222.22	−360.4	−218	−138.89	−90.4	−68	−55.56	179.6	82	27.78	449.6	232	111.11
.....	−366	−221.11	−356.8	−216	−137.78	−86.8	−66	−54.44	183.2	84	28.89	453.2	234	112.22
.....	−364	−220.00	−353.2	−214	−136.67	−83.2	−64	−53.33	186.8	86	30.00	456.8	236	113.33
.....	−362	−218.89	−349.6	−212	−135.56	−79.6	−62	−52.22	190.4	88	31.11	460.4	238	114.44
.....	−360	−217.78	−346.0	−210	−134.44	−76.0	−60	−51.11	194.0	90	32.22	464.0	240	115.56
.....	−358	−216.67	−342.4	−208	−133.33	−72.4	−58	−50.00	197.6	92	33.33	467.6	242	116.67
.....	−356	−215.56	−338.8	−206	−132.22	−68.8	−56	−48.89	201.2	94	34.44	471.2	244	117.78
.....	−354	−214.44	−335.2	−204	−131.11	−65.2	−54	−47.78	204.8	96	35.56	474.8	246	118.89
.....	−352	−213.33	−331.6	−202	−130.00	−61.6	−52	−46.67	208.4	98	36.67	478.4	248	120.00
.....	−350	−212.22	−328.0	−200	−128.89	−58.0	−50	−45.56	212.0	100	37.78	482.0	250	121.11
.....	−348	−211.11	−324.4	−198	−127.78	−54.4	−48	−44.44	215.6	102	38.89	485.6	252	122.22
.....	−346	−210.00	−320.8	−196	−126.67	−50.8	−46	−43.33	219.2	104	40.00	489.2	254	123.33
.....	−344	−208.89	−317.2	−194	−125.56	−47.2	−44	−42.22	222.8	106	41.11	492.8	256	124.44
.....	−342	−207.78	−313.6	−192	−124.44	−43.6	−42	−41.11	226.4	108	42.22	496.4	258	125.56
.....	−340	−206.67	−310.0	−190	−123.33	−40.0	−40	−40.00	230.0	110	43.33	500.0	260	126.67
.....	−338	−205.56	−306.4	−188	−122.22	−36.4	−38	−38.89	233.6	112	44.44	503.6	262	127.78
.....	−336	−204.44	−302.8	−186	−121.11	−32.8	−36	−37.78	237.2	114	45.56	507.2	264	128.89
.....	−334	−203.33	−299.2	−184	−120.00	−29.2	−34	−36.67	240.8	116	46.67	510.8	266	130.00
.....	−332	−202.22	−295.6	−182	−118.89	−25.6	−32	−35.56	244.4	118	47.78	514.4	268	131.11
.....	−330	−201.11	−292.0	−180	−117.78	−22.0	−30	−34.44	248.0	120	48.89	518.0	270	132.22
.....	−328	−200.00	−288.4	−178	−116.67	−18.4	−28	−33.33	251.6	122	50.00	521.6	272	133.33
.....	−326	−198.89	−284.8	−176	−115.56	−14.8	−26	−32.22	255.2	124	51.11	525.2	274	134.44
.....	−324	−197.78	−281.2	−174	−114.44	−11.2	−24	−31.11	258.8	126	52.22	528.8	276	135.56
.....	−322	−196.67	−277.6	−172	−113.33	−7.6	−22	−30.00	262.4	128	53.33	532.4	278	136.67
.....	−320	−195.56	−274.0	−170	−112.22	−4.0	−20	−28.89	266.0	130	54.44	536.0	280	137.78
.....	−318	−194.44	−270.4	−168	−111.11	−0.4	−18	−27.78	269.6	132	55.56	539.6	282	138.89
.....	−316	−193.33	−266.8	−166	−110.00	+3.2	−16	−26.67	273.2	134	56.67	543.2	284	140.00
.....	−314	−192.22	−263.2	−164	−108.89	+6.8	−14	−25.56	276.8	136	57.78	546.8	286	141.11
.....	−312	−191.11	−259.6	−162	−107.78	+10.4	−12	−24.44	280.4	138	58.89	550.4	288	142.22
.....	−310	−190.00	−256.0	−160	−106.67	+14.0	−10	−23.33	284.0	140	60.00	554.0	290	143.33

F		C
557.6	292	144.44
561.2	294	145.56
564.8	296	146.67
568.4	298	147.78
572.0	300	148.89
575.6	302	150.00
579.2	304	151.11
582.8	306	152.22
586.4	308	153.33
590.0	310	154.44
593.6	312	155.56
597.2	314	156.67
600.8	316	157.78
604.4	318	158.89
608.0	320	160.00
611.6	322	161.11
615.2	324	162.22
618.8	326	163.33
622.4	328	164.44
626.0	330	165.56
629.6	332	166.67
633.2	334	167.78
636.8	336	168.89
640.4	338	170.00
644.0	340	171.11
647.6	342	172.22
651.2	344	173.33
654.8	346	174.44
658.4	348	175.56
662.0	350	176.67
665.6	352	177.78
669.2	354	178.89
672.8	356	180.00
676.4	358	181.11
680.0	360	182.22
683.6	362	183.33
687.2	364	184.44
690.8	366	185.56
694.4	368	186.67
698.0	370	187.78
701.6	372	188.89
705.2	374	190.00
708.8	376	191.11
712.4	378	192.22
716.0	380	193.33
719.6	382	194.44
723.2	384	195.56
726.8	386	196.67
730.4	388	197.78
734.0	390	198.89
737.6	392	200.00
741.2	394	201.11
744.8	396	202.22
748.4	398	203.33
752.0	400	204.44
755.6	402	205.56
759.2	404	206.67
762.8	406	207.78
766.4	408	208.89
770.0	410	210.00
773.6	412	211.11
777.2	414	212.22
780.8	416	213.33
784.4	418	214.44
788.0	420	215.56
791.6	422	216.67
795.2	424	217.78
798.8	426	218.89
802.4	428	220.00
806.0	430	221.11
809.6	432	222.22
813.2	434	223.33
816.8	436	224.44
820.4	438	225.56
824.0	440	226.67
827.6	442	227.78
831.2	444	228.89
834.8	446	230.00
838.4	448	231.11
842.0	450	232.22
845.6	452	233.33
849.2	454	234.44
852.8	456	235.56
856.4	458	236.67
860.0	460	237.78
863.6	462	238.89
867.2	464	240.00

F		C
870.8	466	241.11
874.4	468	242.22
878.0	470	243.33
881.6	472	244.44
885.2	474	245.56
888.8	476	246.67
892.4	478	247.78
896.0	480	248.89
899.6	482	250.00
903.2	484	251.11
906.8	486	252.22
910.4	488	253.33
914.0	490	254.44
917.6	492	255.56
921.2	494	256.67
924.8	496	257.78
928.4	498	258.89
932.0	500	260.00
935.6	502	261.11
939.2	504	262.22
942.8	506	263.33
946.4	508	264.44
950.0	510	265.56
953.6	512	266.67
957.2	514	267.78
960.8	516	268.89
964.4	518	270.00
968.0	520	271.11
971.6	522	272.22
975.2	524	273.33
978.8	526	274.44
982.4	528	275.56
986.0	530	276.67
989.6	532	277.78
993.2	534	278.89
996.8	536	280.00
1000.4	538	281.11
1004.0	540	282.22
1007.6	542	283.33
1011.2	544	284.44
1014.8	546	285.56
1018.4	548	286.67
1022.0	550	287.78
1040.0	560	293.33
1058.0	570	298.89
1076.0	580	304.44
1094.0	590	310.00
1112.0	600	315.56
1130.0	610	321.11
1148.0	620	326.67
1166.0	630	332.22
1184.0	640	337.78
1202.0	650	343.33
1220.0	660	348.89
1238.0	670	354.44
1256.0	680	360.00
1274.0	690	365.56
1292.0	700	371.11
1310.0	710	376.67
1328.0	720	382.22
1346.0	730	387.78
1364.0	740	393.33
1382.0	750	398.89
1400.0	760	404.44
1418.0	770	410.00
1436.0	780	415.56
1454.0	790	421.11
1472.0	800	426.67
1490.0	810	432.22
1508.0	820	437.78
1526.0	830	443.33
1544.0	840	448.89
1562.0	850	454.44
1580.0	860	460.00
1598.0	870	465.56
1616.0	880	471.11
1634.0	890	476.67
1652.0	900	482.22
1670.0	910	487.78
1688.0	920	493.33
1706.0	930	498.89
1724.0	940	504.44
1742.0	950	510.00
1760.0	960	515.56
1778.0	970	521.11
1796.0	980	526.67
1814.0	990	532.22

F		C
1832.0	1000	537.78
1850.0	1010	543.33
1868.0	1020	548.89
1886.0	1030	554.44
1904.0	1040	560.00
1922.0	1050	565.56
1940.0	1060	571.11
1958.0	1070	576.67
1976.0	1080	582.22
1994.0	1090	587.78
2012.0	1100	593.33
2030.0	1110	598.89
2048.0	1120	604.44
2066.0	1130	610.00
2084.0	1140	615.56
2102.0	1150	621.11
2120.0	1160	626.67
2138.0	1170	632.22
2156.0	1180	637.78
2174.0	1190	643.33
2192.0	1200	648.89
2210.0	1210	654.44
2228.0	1220	660.00
2246.0	1230	665.56
2264.0	1240	671.11
2282.0	1250	676.67
2300.0	1260	682.22
2318.0	1270	687.78
2336.0	1280	693.33
2354.0	1290	698.89
2372.0	1300	704.44
2390.0	1310	710.00
2408.0	1320	715.56
2426.0	1330	721.11
2444.0	1340	726.67
2462.0	1350	732.22
2480.0	1360	737.78
2498.0	1370	743.33
2516.0	1380	748.89
2534.0	1390	754.44
2552.0	1400	760.00
2570.0	1410	765.56
2588.0	1420	771.11
2606.0	1430	776.67
2624.0	1440	782.22
2642.0	1450	787.78
2660.0	1460	793.33
2678.0	1470	798.89
2696.0	1480	804.44
2714.0	1490	810.00
2732.0	1500	815.56
2750.0	1510	821.11
2768.0	1520	826.67
2786.0	1530	832.22
2804.0	1540	837.78
2822.0	1550	843.33
2840.0	1560	848.89
2858.0	1570	854.44
2876.0	1580	860.00
2894.0	1590	865.56
2912.0	1600	871.11
2930.0	1610	876.67
2948.0	1620	882.22
2966.0	1630	887.78
2984.0	1640	893.33
3002.0	1650	898.89
3020.0	1660	904.44
3038.0	1670	910.00
3056.0	1680	915.56
3074.0	1690	921.11
3092.0	1700	926.67
3110.0	1710	932.22
3128.0	1720	937.78
3146.0	1730	943.33
3164.0	1740	948.89
3182.0	1750	954.44
3200.0	1760	960.00
3218.0	1770	965.56
3236.0	1780	971.11
3254.0	1790	976.67
3272.0	1800	982.22
3290.0	1810	987.78
3308.0	1820	993.33
3326.0	1830	998.89
3344.0	1840	1004.4
3362.0	1850	1010.0
3380.0	1860	1015.6

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3398.0	1870	1021.1
3416.0	1880	1026.7
3434.0	1890	1032.2
3452.0	1900	1037.8
3470.0	1910	1043.3
3488.0	1920	1048.9
3506.0	1930	1054.4
3524.0	1940	1060.0
3542.0	1950	1065.6
3560.0	1960	1071.1
3578.0	1970	1076.7
3596.0	1980	1082.2
3614.0	1990	1087.8
3632.0	2000	1093.3
3650.0	2010	1098.9
3668.0	2020	1104.4
3686.0	2030	1110.0
3704.0	2040	1115.6
3722.0	2050	1121.1
3740.0	2060	1126.7
3758.0	2070	1132.2
3776.0	2080	1137.8
3794.0	2090	1143.3
3812.0	2100	1148.9
3830.0	2110	1154.4
3848.0	2120	1160.0
3866.0	2130	1165.6
3884.0	2140	1171.1
3902.0	2150	1176.7
3920.0	2160	1182.2
3938.0	2170	1187.8
3956.0	2180	1193.3
3974.0	2190	1198.9
3992.0	2200	1204.4
4010.0	2210	1210.0
4028.0	2220	1215.6
4046.0	2230	1221.1
4064.0	2240	1226.7
4082.0	2250	1232.2
4100.0	2260	1237.8
4118.0	2270	1243.3
4136.0	2280	1248.9
4154.0	2290	1254.4
4172.0	2300	1260.0
4190.0	2310	1265.6
4208.0	2320	1271.1
4226.0	2330	1276.7
4244.0	2340	1282.2
4262.0	2350	1287.8
4280.0	2360	1293.3
4298.0	2370	1298.9

F		C
4964.0	2740	1504.4
4982.0	2750	1510.0
5000.0	2760	1515.6
5018.0	2770	1521.1
5036.0	2780	1526.7
5054.0	2790	1532.2
5072.0	2800	1537.8
5090.0	2810	1543.3
5108.0	2820	1548.9
5126.0	2830	1554.4
5144.0	2840	1560.0
5162.0	2850	1565.6
5180.0	2860	1571.1
5198.0	2870	1576.7
5216.0	2880	1582.2
5234.0	2890	1587.8
5252.0	2900	1593.3
5270.0	2910	1598.9
5288.0	2920	1604.4
5306.0	2930	1610.0
5324.0	2940	1615.6
5342.0	2950	1621.1
5360.0	2960	1626.7
5378.0	2970	1632.2
5396.0	2980	1637.8
5414.0	2990	1643.3
5432.0	3000	1648.9
5450.0	3010	1654.4
5468.0	3020	1660.0
5486.0	3030	1665.6
5504.0	3040	1671.1
5522.0	3050	1676.7
5540.0	3060	1682.2
5558.0	3070	1687.8
5576.0	3080	1693.3
5594.0	3090	1698.9
5612.0	3100	1704.4
5702.0	3150	1732.2
5792.0	3200	1760.0
5882.0	3250	1787.7
5972.0	3300	1815.5
6062.0	3350	1843.3
6152.0	3400	1871.1
6242.0	3450	1898.8
6332.0	3500	1926.6
6422.0	3550	1954.4
6512.0	3600	1982.2
6602.0	3650	2010.0
6692.0	3700	2037.7
6782.0	3750	2065.5
6872.0	3800	2093.3